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TECHNICAL REPORT H-76-17

SLUICE PRESSURES, GATE VIBRATIONS AND STILLING BASIN WALL PRESSURES LIBBY DAM, KOOTENAI RIVER, MONTANA

by

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P. O. Box 631, Vicksburg, Miss. 39180

October 1976
Final Report

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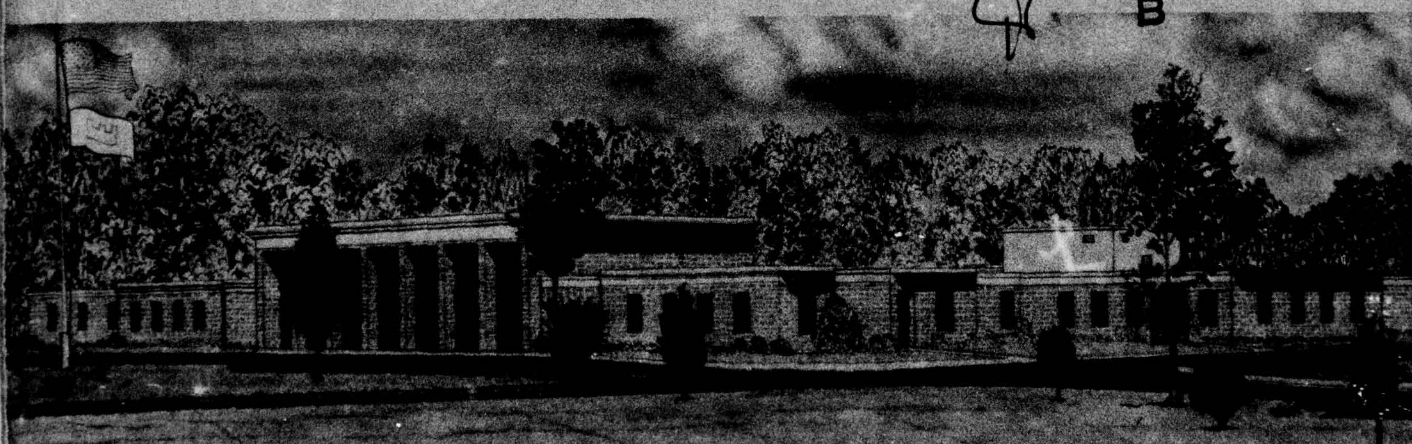

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Two of the three Libby Dam sluices suffered cavitation damage after a short period of operation. During this period of operation, extreme noise was heard and structural movement suspected.

Prototype studies were conducted to monitor the sluice pressure fluctuation amplitudes and frequencies as well as sluice gate and structural vibrations. In addition, stilling basin wall pressures were measured during spillway releases. cont on next page

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20. ABSTRACT (Continued).

The sluice pressure measurements indicated that negative pressure fluctuations occurred at all points of measurement along the invert (at all gate openings) and that vapor pressure was approached or occurred at three of these locations during certain gate openings. Structural vibrations were generally insignificant whereas the sluice gate was subjected to significant vibrations in all three directions. The mean pressures measured on the stilling basin wall were lower in the upstream, lower portion of the wall and vapor pressure was approached in the upstream lower corner.

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PREFACE

The prototype tests described in this report were conducted during July and August of 1974. They were made by the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U. S. Army Engineer District, Seattle.

Acknowledgment is made to the individuals of the Seattle District who actively participated in this investigation. Mr. E. D. Hart, Chief of the Prototype Branch, was test coordinator for WES. This report was prepared by Mr. Hart with the assistance of Mr. A. R. Tool under the general supervision of Mr. E. B. Pickett, Chief of the Hydraulic Analysis Division, and Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, WES.

COL G. H. Hilt, CE, and COL John L. Cannon, CE, were Directors of WES during the investigation and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
acre-feet	1233.482	cubic metres
pounds (force) per square inch	6894.757	pascals
inches per second	2.54	centimetres per second
feet per second per second	0.3048	metres per second per second
cubic feet per second	0.02831685	cubic metres per second

SLUICE PRESSURES, GATE VIBRATIONS, AND STILLING BASIN WALL PRESSURES, LIBBY DAM, KOOTENAI RIVER, MONTANA

PART I: INTRODUCTION

Pertinent Features of the Project

1. The multipurpose Libby Dam and Reservoir (Figure 1) is located in northwestern Montana on the Kootenai River, approximately 17 miles* upstream from Libby, Montana; the damsite is at river mile 219 (Figure 2). Primary purposes of the project are flood control, power and recreation.

2. The concrete gravity dam is 2955 ft long at the top, rising 336 ft above the streambed. The power plant will eventually consist of eight power units, with 20-ft-diam penstocks and a plant capacity of 840,000 kw. The dam impounds 5,850,000 acre-feet of water in Lake Koocanusa at full pool (el 2459.0 ft msl**).

Outlet Works

3. Desired flow through the structure is accomplished by means of a two-bay ogee spillway over which flow is controlled by two 48-ft-wide by 56-ft-high tainter gates; three sluices, each 10 ft wide by 22 ft high, controlled by 10-ft-wide by 17-ft-high tainter gates; and the stilling basin at el 2073.0. Both the spillway and sluices empty into the same hydraulic-jump type stilling basin (Figure 3) with sloping end sill and no baffles. Pertinent elevations and dimensions are shown in Plate 1.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

** All elevations (el) cited herein are in feet above mean sea level (msl).

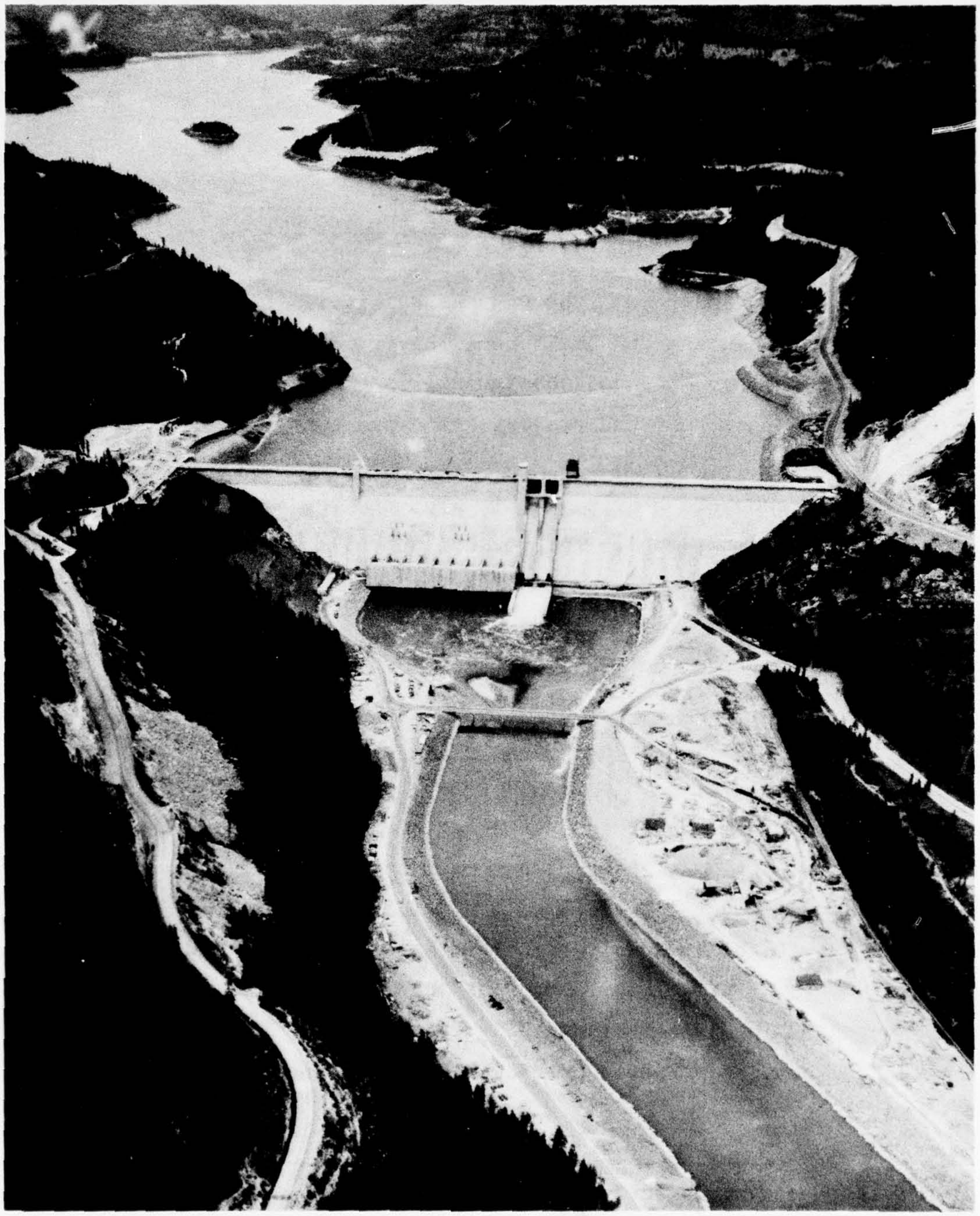


Figure 1. Libby Dam and Reservoir

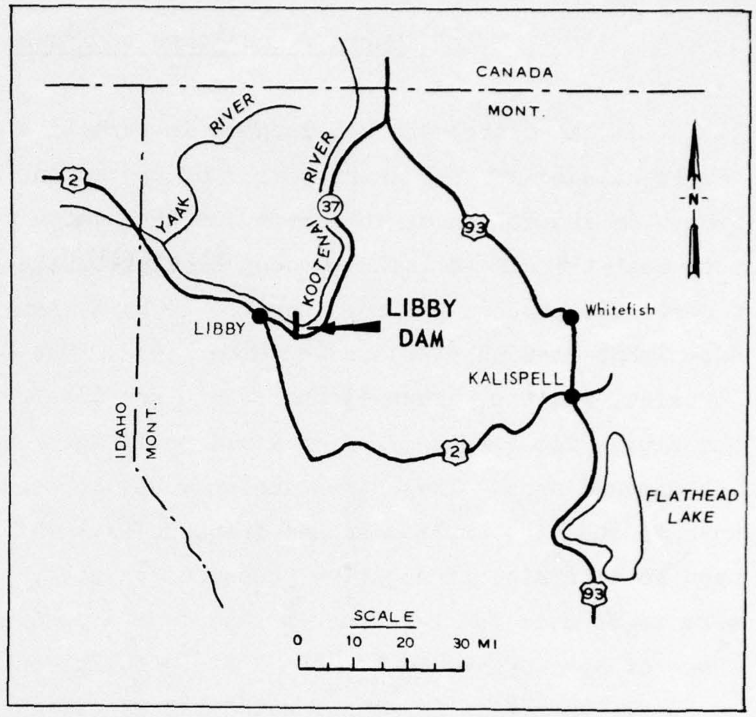


Figure 2. Vicinity map

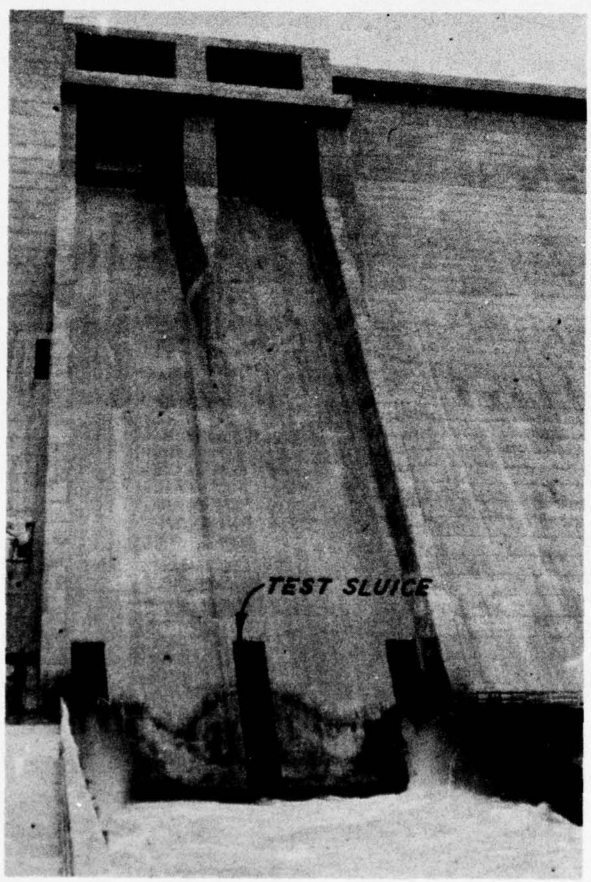


Figure 3. Stilling basin, spillway, and sluice portals

Purpose and Scope of Tests

4. The center sluice, located in structure monolith 29, was severely damaged after a short period of operation, apparently by cavitation. An indication of the extent of the damage is given in Figure 4; note that the damage included deep erosion of the wall as well as the floor. The problem was reported to the U. S. Army Engineer Waterways Experiment Station (WES) in September 1973. The U. S. Army Engineer District, Seattle, proposed that WES place nine pressure transducers in the sluice floor, six of which would be in the reconstructed surface of the damaged area. These transducers would be used to monitor the pressure fluctuation amplitudes and frequencies. This information would be used to determine if negative pressures existed. These measurements were to be made for 1-ft increments of gate openings and closings. The range of openings would be from 1 ft to fully open (17.0 ft).

5. Operation personnel had detected extreme noise and suspected structural movement during large sluice gate openings. For these reasons, accelerometer measurements were requested by the Seattle District

Figure 4. Erosion damage, center sluice, looking downstream

to determine vibrational frequency and magnitude for the center sluice gate and the surrounding concrete structure. The measurements were to be made at 1-ft movements of gate opening, beginning with the opening which initiated a significant response. Continuous recordings were also to be made as the gate was opening and closing.

6. Prior to construction of the project, WES proposed installing five pressure transducer carriage-guide slots in the stilling basin wall for pressure fluctuation measurements. Since Libby Dam has no baffle piers, it was thought the data would be valuable for comparison with information obtained from a prototype basin with baffles.[1] Also, to allow comparison with model data, the pressure measurements were to be made at elevations that corresponded with those of the Libby Dam model tests which were conducted by the North Pacific Division Hydraulics Laboratory.[2]

PART II: TEST FACILITIES, EQUIPMENT, AND PROCEDURES

Test Facilities

Sluice pressures

7. Nine pressure transducer mounting boxes were installed in the floor of the center sluice as shown in Plate 1. The surface plate of each box was installed flush with the invert surface. Two interchangeable cover plates were fabricated for each mounting box, one for a permanent cover and the other for WES to install the pressure transducer just prior to testing. Six were located along the center line on the invert and three on the invert near the right wall in the area that experienced the most severe damage. A typical installed plate with its pressure transducers mounted is shown in Figure 5.

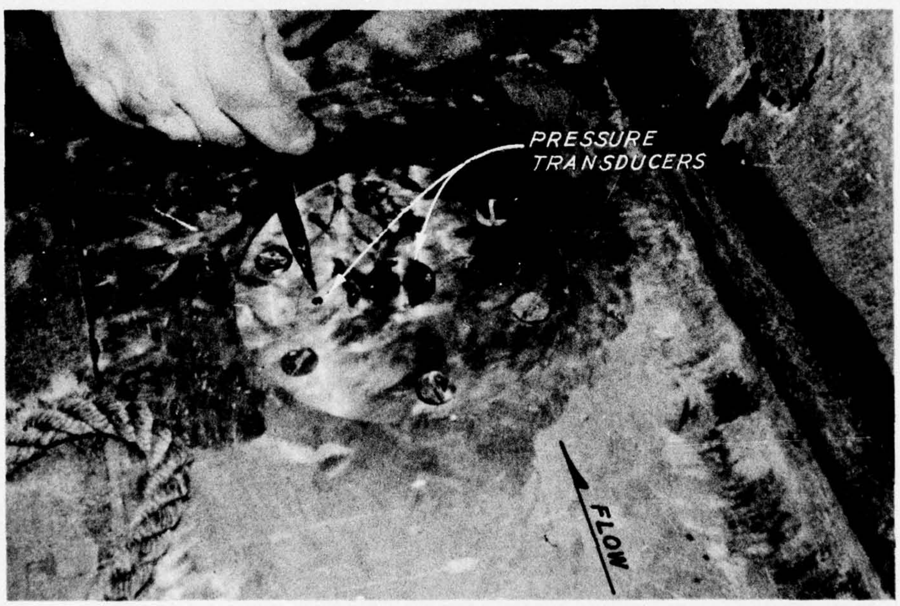


Figure 5. Installed cover plate and pressure transducers in sluice floor

8. The transducer cables passed from the test sluice through holes drilled from the base of the mounting boxes downward into the drainage gallery at el 2081.5 (Plate 1). Six of the cables (3, 3A, 4,

4A, 5, and 5A) passed through a common hole in the base of transducer 4 mounting box; the others passed through individual holes. Figure 6 shows the cable being fed through mounting box 6.

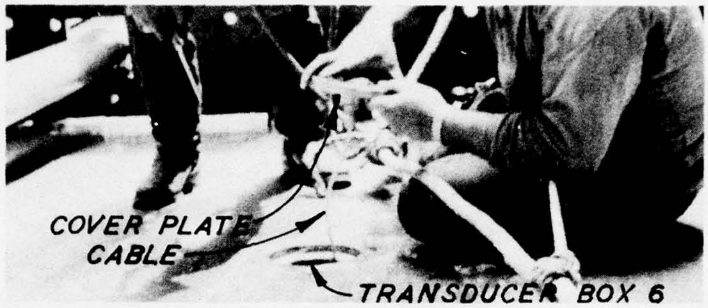


Figure 6. Installation of pressure transducer 6

Gate vibrations

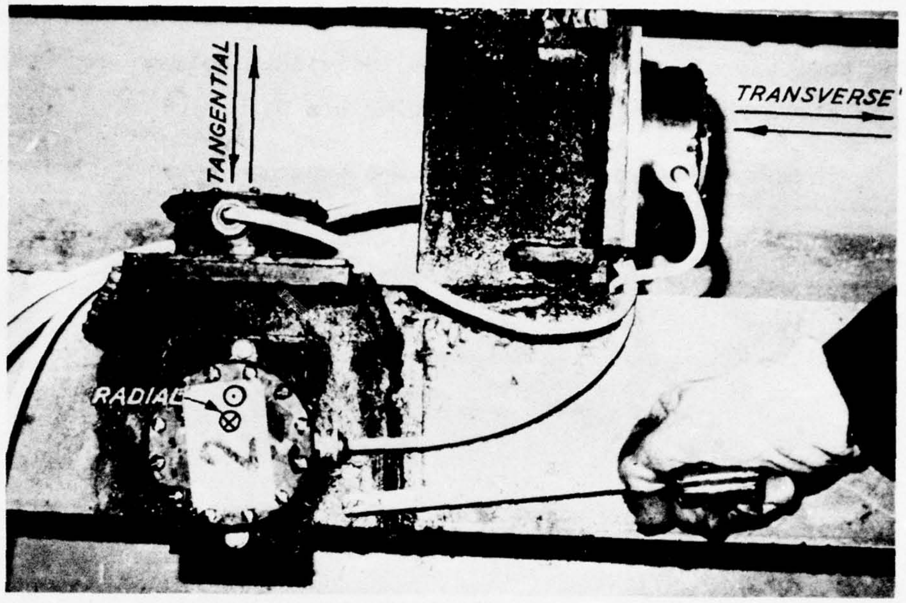
9. Special plates were welded to the back side of the center sluice tainter gate for installing accelerometers. These plates were installed under the supervision of WES personnel just prior to the tests. A cluster of three accelerometers (radial, tangential, and transverse) was then attached to the plates. A corresponding cluster was located directly over the center sluice on the dam gallery floor at el 2240.25 (Plate 1). Figures 7a and 7b show the clusters on the gate and gallery floor, respectively; their general locations are shown in Plate 1.

Stilling basin wall pressures

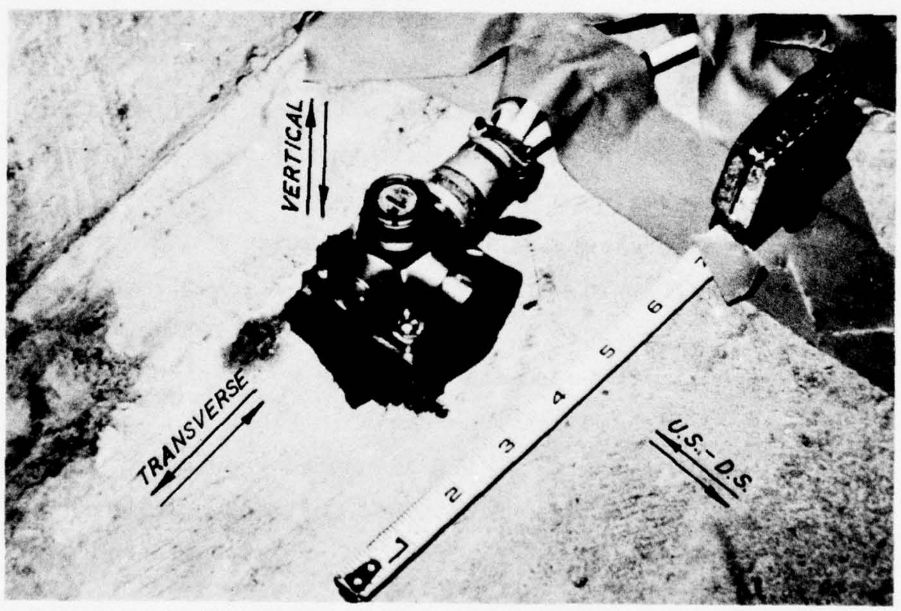
10. Five pressure transducer carriage-guide slots were embedded in the right stilling basin wall during construction (Plate 1). The pressure transducers, mounted in special carriages fabricated at WES, were initially set at el 2083.0 and then were moved simultaneously up the slot to the other desired elevations shown in Plate 1. The transducers were held at each elevation while the discharge was varied. In this manner, an array of pressures was obtained for each spillway discharge. Figure 8 shows the carriage and the mounted pressure transducer.

Test Equipment

11. The test equipment described herein includes the transducers,



a. Accelerometers attached to center sluice control gate



b. Accelerometers attached to structure floor at el 2240.45

Figure 7. Clusters of accelerometers on gate and gallery floor

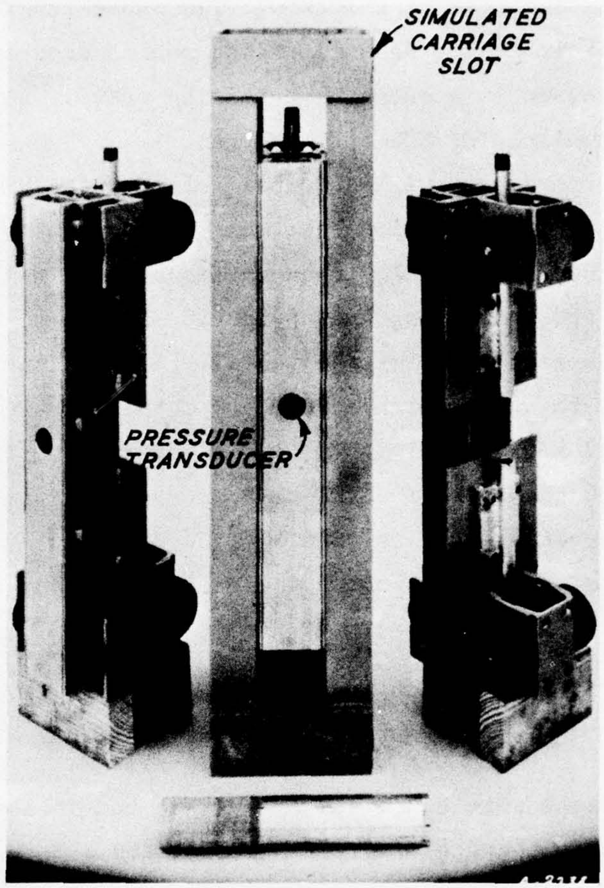


Figure 8. Stilling basin wall pressure transducer carriage

cables, and recording equipment. Transducers used for the tests were as follows:

- a. Sluice pressure tests: 50- to 2000-psia pressure transducers.
- b. Vibration tests: ±5g accelerometers.
- c. Stilling basin wall pressure tests: 100-psia pressure transducers.

Table 1 lists the transducer type, range, location, and function.

12. Cable lengths required for the test program were determined from contract drawings of the project. These cable lengths were cut and used in the pretest and posttest calibration of their corresponding

transducers to account for line losses. The cable length for each transducer is given in Table 1. In some cases, cables used in one phase of the tests were reused in a subsequent testing phase. Almost 2.7 miles of cable were required for the test program.

13. The recording equipment consisted of: (a) WES-fabricated model 01 amplifiers to condition the transducer output signal, (b) a Sangamo model 3500, 14-channel, frequency modulated, magnetic-tape recorder with a frequency response up to 2.5 kHz at 7.5 ips and 20 kHz at 60 ips (tape speeds used for the tests), (c) a Century model 541 galvanometer driver to supply higher current to the high-frequency galvanometers, and (d) a CEC model 1-119, 12-in. chart, oscillograph capable of reproducing 36 channels of data at a paper speed from 0.25 ips to 160 ips at a frequency response of 0 to 2500 Hz. (Speeds used at Libby were 4 and 40 ips.) Figure 9 shows the equipment setup at the recording station.

Test Procedures

14. The tests were conducted in 1974 in the following sequence: (a) sluice pressure tests (31 July-2 August), (b) gate vibration tests

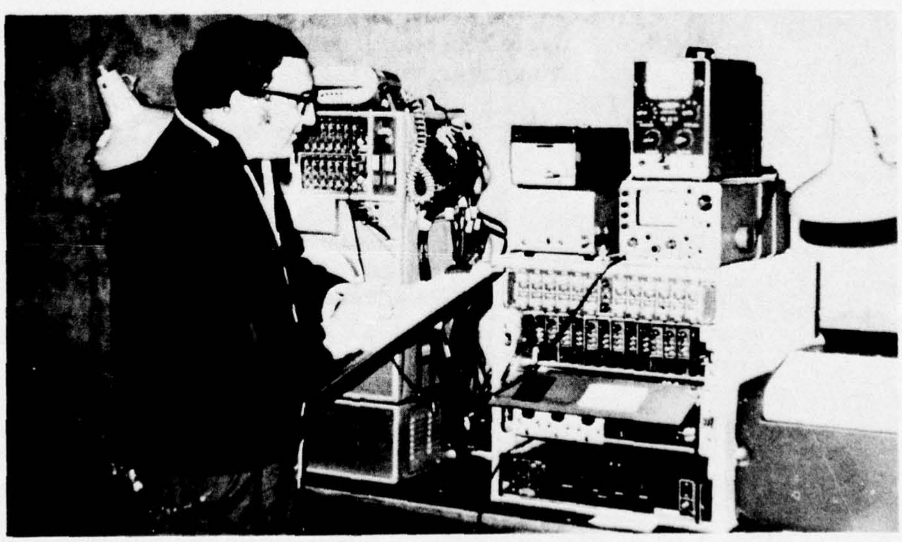


Figure 9. Recording station and equipment

(3 August), and (c) stilling basin wall pressure tests (5-6 August). All were recorded on magnetic tape. During each individual test, a portion of the taped data was transferred to the oscillogram to confirm that the data were being recorded and to make a visual check of the results.

15. Procedure was generally the same for all three test phases and consisted of the following with all personnel on station:

a. Record test number, date, time, and conditions.

b. Record zero (no flow).

c. Record step calibrations.

d. Raise test gate to desired opening; allow flow to stabilize.

e. Record data on tape and oscillograph at speeds given in paragraph 13.

f. Measure discharge (Seattle District).

g. Record upper pool and tailwater elevations.

h. Record air and water temperatures.

i. Record step calibration.

16. Voice comments on the tape and notes on the oscillograph were continuously made for later reference. Gain changes, to improve the recorded signal, and corresponding calibrations were made as required during the test period.

PART III: TEST RESULTS AND ANALYSIS

Sluice Pressures

17. Eighteen pressure tests were conducted in the center sluice. Measurements were made during gate movement and at 1-ft increments with gate openings of 1.0 to 16.0 ft, and then at 16.5 ft. The final measurement was with the gate closing from 16.9 to 16.5 ft. The highest, lowest, and mean pressures were extracted from the oscillograph charts (Table 2 and Plates 2-7); also determined was the maximum instantaneous peak-to-peak pressure fluctuation for each test.

18. As indicated in Table 2, during all tests each transducer recorded negative pressures (except in the cases when the transducers were not operative. As shown in Table 2 and Plates 2-7, almost all the mean pressures at each transducer varied over a narrow range of negative pressures, regardless of the gate opening. The smallest mean pressure occurred at transducer sta 1 with a variance from -3 to -5 ft of water; at sta 6, the range was from -4 to -14 ft of water.

19. The accuracy of these listed pressures is dependent upon at least three factors: (a) accuracy of reading the oscillograph traces, (b) basic transducer accuracy, and (c) transducer accuracy improvement due to calibration. The estimated accuracy for these tests varied from ±0.5 ft for the low range (50 psia) transducer to ±2.5 ft for the high range (1000 psia) transducers at a pressure of 20 ft of water. The high range transducers (see Table 1) were selected to ensure adequate pressure range coverage in the violent fluctuations associated with cavitation. The test results indicate that a maximum range of 100 psia would have been adequate and thereby provided more accurate data.

20. As part of the overall investigation, the sluice invert was surveyed in November 1974 at 1-ft increments along its length and at 2-ft intervals in the transverse direction (Plate 8). The survey confirmed what was observed by visual inspection: the invert did not conform to a smooth parabolic shape, varying by as much as 0.2 ft; rather, it tended to follow a series of chords along the theoretical surface.

This being the case, it is possible that the recorded pressures were affected by the transducer location with regard to the sudden slope changes of the invert. The following tabulation lists the slopes preceding and at the transducer location and is arranged so that the transducer lies between sta 2 and 3 for each case (see also Figure 10).

Transducer No.	Sta 1 El	Sta 2 El	Transducer Loc, x	Sta 3 El	Δy = Slope 1-2	2-3	Comments on Installation
1	2185.92	2185.69	0.50	2185.40	0.30	0.29	Very slight U.S. plate protrusion
2	2172.43	2172.20	0.35	2171.83	0.23	0.37	Plate protruding U. S. 1/32 in. or less
3	2162.06	2161.54	0.60	2161.09	0.52	0.45	Plate and lead screw protruding U.S. 1/32 in. or less
3A	2162.00	2161.60	0.90	2161.14	0.40	0.46	Plate and lead screw protruding U.S. 1/32 in. or less
4	2156.86	2156.45	0.22	2155.98	0.41	0.47	Plate protruding U.S. slightly
4A	2156.89	2156.46	0.10	2156.00	0.43	0.46	Smooth
5	2149.72	2149.28	0.30	2148.82	0.44	0.46	Plate and lead screw protruding very slightly
5A	2149.76	2149.30	0.10	2148.82	0.46	0.48	Smooth
6	2130.74	2130.21	0.50	2129.65	0.53	0.56	Plate protruding U.S. 1/32 in. or less

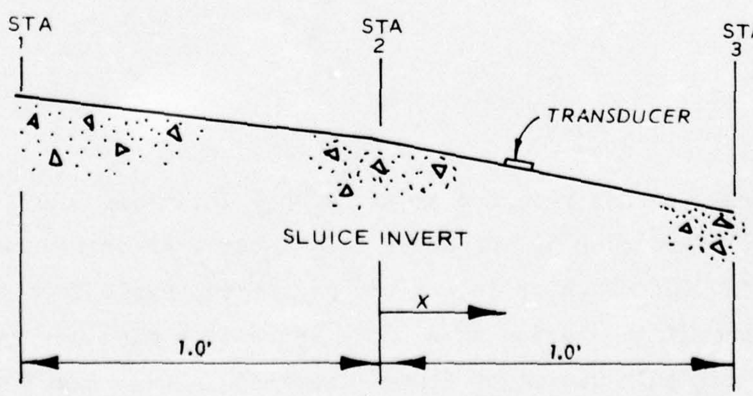


Figure 10. Invert slope relative to transducer location

21. The worst condition would exist when slope 1-2 was substantially smaller than slope 2-3 and with the transducer located just downstream from sta 2. This combination of conditions is most noticeable at transducer 2. Since other transducers measured, on the average, lower pressures than transducer 2, it cannot be concluded that the invert profile affected the pressure readings. In addition to the irregularities cited above, there appeared to be a chordal effect between horizontal construction joints. The relative positions of the construction joints and the transducers are shown in Plate 8.

22. The field notes on transducer installation indicate that there was a slight upstream protrusion of transducer plate 2 which could possibly have affected the pressure recordings also. However, transducers installed "smooth" averaged lower pressures, in a number of cases, than those installed with upstream protrusions. For this reason, it is assumed that the installation of the transducer plates was adequate and did not significantly affect flow conditions.

23. For the cavitation conditions occurring at Libby Dam during the period of the tests, a pressure recording of -30.7 ft represents vapor pressure of the water in the sluice.[3] This value was reached or approached at minimums in the pressure fluctuations during four tests as follows:

Gate Opening, ft	Pressure Transducers Recording ≃ -31 ft
1.0	4,5
5.0	3
11.0	3
15.0	3

Vapor pressure was then recorded at transducer locations 3 and 4, and approached at transducer 5. Pressure fluctuations at transducer 3 are illustrated in Plate 9 which is a 1-sec digitized sample from the magnetic tape recording. During this short interval a minimum pressure of -23 ft was recorded. The major damage occurred between sta 3 and 5

(Plate 1). It is possible that initial erosion due to the low pressures occurred near the location of transducer 3. This irregularity may have then intensified the cavitation and caused erosion to progress downstream.

24. The cavitation indices listed in Table 2 were calculated using the equation

$$K_i = \frac{h_i - h_v}{\left(\overline{V}^2/2g\right)_i}$$

where

K_i = cavitation index at transducer i

h_i = mean absolute pressure at transducer i, ft

h_v = vapor pressure, ft

$\left(\overline{V}^2/2g\right)_i$ = velocity head at transducer i, ft

The average velocity $\overline{V}_i$ was determined from the continuity equation $\overline{V} = Q/A$, having calculated depth by the step method.[3,4] Although there is no incipient cavitation index for reference, Table 2 indicates that the indices generally decrease with gate opening (i.e., tend toward cavitation). Since the pressures did not necessarily decrease with gate opening and also varied over a small range (paragraph 18), the downward trend is attributed to an increasing velocity head with gate opening. Because of the questionable accuracy of the water depth calculations, the indices are presented as relative rather than absolute indicators.

Structural Vibrations

25. Structural vibrations were measured on the gallery floor at el 2240.25, sta +60 (directly above the center sluice), as shown in Plate 1. These measurements were insignificant in almost all tests. During the continuous gate opening from 16.0 to 16.5 ft, maximum peak-to-peak amplitudes were recorded on the oscillogram for all three accelerometers of the cluster. These maximum recordings and corresponding displacements were as follows:

Direction	Peak-to-Peak Amplitude, g's	Frequency Hz	Displacement* μ ft
Vertical	0.035	140	0.03
Upstream/ Downstream	0.045	140	0.04
Transverse	0.047	140	0.04

* μ ft = 0.000001 ft; displacements estimated by the sinusoidal equation $d = \text{acceleration}/(2\Pi \text{freq})^2$.

Because of the higher frequencies of these accelerations, the computed displacements were less than those shown in Table 3 for gate openings of 15.0 and 15.5 ft, even though the recorded amplitudes listed above were larger.

Gate Vibrations

26. The accelerometers were installed on the control gate of the center sluice as described in paragraph 9. The analysis included data from the oscillograms and the magnetic tapes. Table 3 contains a summary of data taken from each source. The reduction and analysis of the magnetic tapes included digitizing the data and transforming it from the recorded time domain into the frequency domain. This manipulation is referred to as time series analysis and is the equivalent of a mathematical Fourier Transform (or Fast Fourier Transform, abbreviated FFT). This display presents the frequencies at which maximum energy is concentrated for a particular parameter, such as acceleration.

27. In the time series analysis, 1- and 4-sec samples were reduced from 10 of the accelerometer tests recorded on magnetic tape. The upper cutoff frequency f_c for this analysis was chosen to be 500 Hz. To avoid aliasing the original data,[5] the time interval (Δt) between samples should be no greater than $1/(2f_c)$. Therefore, Δt was chosen to be 0.001 sec. Typical replots of the digitized data are shown in Plates 10-12.

28. The following example comparison of maximum accelerations can be made by listing data from the oscillogram and the time series

analysis. The data come from Record No. 58 of Table 3, gate opening 15.0 ft.

	Oscillogram Analysis			Time Series Analysis				
				Digitized Sample, Peak-to-Peak	FFT			
Direction	Frequency Hz	Peak-to-Peak Amplitude g's	Displacement μ ft	Amplitude g's	Maximum Frequency Hz	0-Peak Amplitude g's	Adjusted Peak-to-Peak g's	Displacement μ ft
Tangential	250	0.43	5.6	0.590	260	0.019	0.190	2.3
Radial	60	0.87	200.0	0.740	56	0.025	0.050	13.0
Transverse	150	0.19	7.0	0.185	44	0.004	0.008	16.8

The maximum accelerations derived from the oscillogram are random peaks which may not have appeared on the 4- or 1-sec segments of the digitized data. Therefore, the digital playback will never contain peaks greater than the corresponding oscillogram recording. The peak accelerations listed under the FFT heading are the maximum coefficients in the Fourier series expansion. Their peak-to-peak value can be approximated by multiplying by 2.

29. The natural frequency of the gate accelerometers is 75 Hz and each accelerometer is damped to 70 percent of critical. In almost all cases, as shown in Table 3, the maximum measured radial and transverse accelerations occur at frequencies less than 75 Hz, therefore requiring no adjustment. On the other hand, tangential accelerations occur at frequencies much larger than the accelerometer natural frequency. The predominant frequencies are also shown in the Fourier Transforms of Plates 10-12. Therefore, these tangential accelerations require adjustment to account for the reduced instrument response due to damping (see adjusted column above).

30. This adjustment can be made by expressing the ratio (magnification factor) of the actual to measured acceleration (Aa/Am) as a function of the frequency ratio (f/fn) and the damping factor (0.7). To adjust the tangential acceleration in the listing of paragraph 28, calculate the frequency ratio $260/75 = 3.47$. From the magnification ratio graph,[6] determine $Aa \approx 5Am$. Then the adjusted peak-to-peak acceleration would be $2 \times 5 \times 0.019 = 0.19$ g's. This corresponds to a displacement of 2.3μ ft at 260 Hz. The radial and transverse

displacements were calculated using recorded accelerations. All three estimated sets of values represent the predominant displacements and frequencies to which the gate is subjected for this particular gate opening during this segment of time.

31. An attempt was made to determine if there was a relationship between the gate vibration frequencies and the frequency of pressure fluctuations of the transducers on the sluice floor. The cross-correlation of two sets of data describes the general dependence of the values of one set of data on the other, in this case the dependence of pressure fluctuations upon gate vibrations. Plate 13 presents the power spectral density plot for tangential acceleration and pressure transducer 5 at a gate opening of 10 ft. Also shown is a plot of the cross spectrum of the two phenomena. A significant peak in the latter plot would imply a correlation at the frequency of the peak. The magnitudes of the cross-spectral density plot are less than those of the pressure fluctuations plot. Since no significant peaks result from the combination, it is assumed that dependence of pressure on vibrations is insignificant.

Stilling Basin Wall Pressures

32. Pressure fluctuation measurements (Plates 14 and 15) by transducers located in the stilling basin wall were described in paragraph 10. The test discharges, as shown in Table 4, were 20,000, 29,000, 37,000, and approximately 47,000 cfs. Considerable damage to the test equipment and railing along the stilling basin wall was experienced at discharges of 37,000 cfs and greater. The test equipment was severely damaged and the railing completely destroyed as the spillway gates were opened in an attempt to reach 50,000 cfs. Because of the damage, the gates were immediately closed and the discharge was estimated to be 47,000 cfs at the time the pressures were recorded. In subsequent tests, the maximum discharge was restricted to 29,000 cfs.

33. The prototype data listed in Table 4 revealed the largest fluctuations in wall pressures to be near the bottom of the basin. The

mean pressures at the upstream end of the stilling basin were lower, and the pressure fluctuations were greater, than those in other parts of the basin. These two observations are presented graphically in Plates 16-21. Plates 16-19 present pressure fluctuations at transducer el 2083.0. These should be compared with the much smaller fluctuations (for the same discharge) with the transducers located at el 2110.0 (Plates 20 and 21). These plates also illustrate the increase in mean pressure and decrease in pressure fluctuations in the downstream direction. The accompanying Fourier Transforms indicate that the predominant frequencies of fluctuation were less than 10 Hz. Table 4 indicates the magnitude of pressure fluctuations was as large as 24 percent of the calculated entering velocity head when the discharge was 37,000 cfs and the pressure transducers were located at el 2083.0 (10 ft above the basin floor). These ratios were smaller at lower discharges. The entering velocity heads listed in Table 4 were calculated using depths determined by the step method[3,5] down the curved portion of the spillway and OCE Category "A" program number 722-F6-RØ-6AF, H6209 was used down the constant slope portion. The k value for roughness used in the calculations was 0.004 for concrete.[7,8]

34. Negative pressures sufficient to approach or reach vapor pressure were recorded at location PC-1 (Plates 1, 14, and 15 and Table 4) for discharges of 29,000 and 37,000 cfs. This location corresponds to an area where damage has been discovered in an inspection subsequent to the prototype tests. Mean pressures at location PC-3 for all discharges were fairly constant, within ± 2 ft of their collective mean. Also, for all tests conducted with pressure transducers located at el 2083.0, mean pressures were the highest at PC-3.

Model-prototype comparison

35. A comparison of model study and prototype data is presented in Table 5. When comparing the model and prototype results, the accuracy of the equipment used to obtain each should be considered. The prototype pressures are assumed to be accurate to within ± 3.8 ft of water. The accuracy was determined using the manufacturer's specifications for the pressure transducers and the resolution of the oscillograph records. The

model pressures were measured with a 25-psia pressure cell. The estimated error varies from ±2 percent at the maximum observed pressure of 76 ft prototype (1.5 ft model) to about ±4 percent at a typical mean pressure of 35 ft prototype (0.7 ft model). Model pressures within the range of ±10 ft prototype would contain considerable error (15 percent and greater). The mean pressures listed in Table 5 for PC-11 to PC-15 are less than the limits of the accuracy of the recording equipment and probably can be considered to be atmospheric. Also, visual inspection revealed these transducer locations to be above the water level except during surges.

36. A comparison of data indicates tailwater depths to be greater in the model study than the prototype for nearly the same discharge if the mean pressures on transducer PC-5 are used as an indicator of the tailwater depth (Plates 14 and 15). A reason for this could be due to the 10,000-cfs powerhouse discharge simulated in the model tests. Another factor could be the differences in model and prototype discharges for model flows of 30,000 and 40,000 cfs (Table 5).

37. Plates 14 and 15 show comparisons of the model-prototype data with the transducers at el 2083.0. A similar comparison for transducer el 2110.0 can be made by referring to Table 5. For the reason stated in paragraph 35 relative to near-atmospheric pressures, a comparison of the data at transducer el 2128.0 is not suggested.

38. The least favorable comparison occurs at transducers PC-3 and PC-4. The prototype pressure is consistently high at PC-3 and low at PC-4 by about 25 percent (using the prototype reading as a base). Consideration should be given to the error stated in paragraph 35 giving a final possible difference of 17-33 percent. This difference could be due to the heavy surge (about 20 ft) experienced in the prototype which apparently was not recorded in the model study.[2] Plate 15 and Table 5 indicate that a negative mean prototype pressure occurred at PC-1 for a discharge of 37,000 cfs while the mean model pressure was positive. The remaining mean PC-1 readings agree to within about ±10 percent. This seems reasonable considering the stated prototype test conditions.

Previous prototype study

39. A model study[9] of pulsating forces on stilling basin sidewalls indicated they could reach magnitudes up to 1.5 times the entering flow velocity head. It was felt that this figure was excessive and should be further investigated. Additional information would be useful in the design of other similar stilling basins.

40. Stilling basin pressure tests similar to those at Libby were conducted at Barren Dam, Kentucky, in April 1965.[1] The stilling basin floor at Barren is 10 ft below the conduit portal invert and contains streamlined baffle piers and an end sill; in contrast, the Libby Dam spillway crest is 322 ft above the stilling basin floor which contains no baffles. Pulsating wall pressure measurements at each of these projects would provide information for two distinctly different structural designs.

41. The fluctuations recorded at Barren were less than 0.3 times the entering velocity head. As shown in Table 4, the maximum ratio recorded at Libby was 0.24. A plot of these ratios is presented in Plate 22. The data indicate that the pressure fluctuation to entering velocity head ratio increased in an upstream direction during the Libby Dam tests (paragraph 33). The same comparison for the Barren data is inconclusive. The majority of the data from the Libby test series indicates that the ratio increases with depth. Again, the comparison for the Barren data is inconclusive. The magnitude of pressure fluctuations at Barren was largest at the upstream location which agrees with the Libby test findings (paragraph 33).

PART IV: CONCLUSIONS

42. The following determinations and conclusions result from analyses of the data reduction of the Libby Dam prototype tests.

43. Sluice pressures:

- a. Negative invert pressures were experienced at all nine transducer locations for all gate openings.
- b. The possibility exists that the chordal invert surface adversely affects the pressure along the sluice floor.
- c. The calculated cavitation indices indicate a general tendency toward cavitation conditions as gate opening increased, primarily due to increasing velocities.
- d. Vapor pressure was approached or occurred at minimums in pressure fluctuations at transducer locations 3, 4, and 5 (in the damage zone) for certain gate openings during the tests.
- e. Transducer 3 indicated vapor pressure at a number of gate openings. The possibility exists that this general area represents the origin of cavitation damage.
- f. The presumed originating damage near transducer 3 probably intensified the downstream low-pressure fluctuations which caused progressive erosion along the sluice invert and right wall.
- g. 100-psia-range pressure transducers would have been adequate for these tests and thereby have provided more accurate results in some cases.

44. Vibrations:

- a. The vibrations computed from measured accelerations on the gallery floor were generally insignificant.
- b. The sluice control gate is subjected to a range of significant accelerations in all three directions.
- c. In the cases of data reduced, the tangential displacement was always much smaller than the radial and transverse. However, the latter two displacements occurred at frequencies about one-fourth that of the tangential frequency.
- d. Data analysis failed to indicate a correlation between downstream pressure fluctuations and the gate vibrations.

45. Stilling basin wall pressures:

- a. The mean pressures were lower in the upstream lower portion of the stilling basin. This agrees with the model and Barren Dam test data.

b. Vapor pressure was approached at sta PC-1 at the higher discharges in the Libby model and prototype tests.

c. Tailwater elevation in the model is greater than in the prototype, probably due to the additional 10,000-cfs powerhouse discharge simulated in the model.

d. A heavy surge, not indicated in the model, occurs at the approximate location of the middle carriage slot.

e. Pressure fluctuations reached a maximum of 24 percent of the entering velocity head in the Libby tests compared with approximately 30 percent in the Barren tests. This ratio increased with depth.

f. Floor and wall erosion is predictable in the lower upstream portion of the stilling basin at high two-gate spillway operations (about 40,000 cfs and greater).

Comments

46. A combined effort between WES and the Seattle District is under way to attempt to alleviate problems discussed. Action being taken includes: (a) contracting a panel of experts on cavitation to study the problem and make recommendations, and (b) conducting a model study by WES to determine the cause (causes) of sluice damage and to recommend remedial measures.

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Table 1

Instrumentation

Code	Instrument Type*	Instrument Range	Location of Instruments** Sta	Location of Instruments** El	Cable Length ft	Function Measurement	Function Test No.	Comments
1	CEC 4-312	50 psia	0+78.4	2185.5	538	Sluice pressure	1-64	Test numbers include calibrations and static conditions
2	CEC 4-312	150 psia	1+21.2	2172.0	538	Sluice pressure	1-64	
3	CEC 4-313	1000 psia	1+49.5	2161.1	533	Sluice pressure	1-64	
3K	Kistler 603A	1000 psia	1+49.5	2161.1	533	Sluice pressure	1-49	Grounding problem affected output
3A	CEC 4-313	2000 psia	1+49.5	2161.1	538	Sluice pressure	1-15	
3A	CEC 4-313	500 psia	1+49.5	2161.1	538	Sluice pressure	16-49	
4	CEC 4-313	1000 psia	1+61.1	2156.3	548	Sluice pressure	1-64	
4A	CEC 4-313	1000 psia	1+61.1	2156.3	580	Sluice pressure	1-64	
4AK	Kistler 603A	1000 psia	1+61.1	2156.3	580	Sluice pressure	1-49	Grounding problem affected output
5	CEC 4-313	1000 psia	1+77.2	2149.0	568	Sluice pressure	1-64	
5A	CEC 4-313	2000 psia	1+77.2	2149.0	578	Sluice pressure	1-15	
5A	CEC 4-313	500 psia	1+77.2	2149.0	578	Sluice pressure	16-49	
6	CEC 4-312	150 psia	2+15.4	2130.2	568	Sluice pressure	1-49	
GV	Statham A3	5 g's	Center sluice gate		580	Gate acceleration--tangential	50-64	
GR	Statham A3	5 g's	Center sluice gate		578	Gate acceleration--radial	50-64	
GT	Statham A3	5 g's	Center sluice gate		568	Gate acceleration--transverse	50-64	
FV	CEC 4-2-4-001	5 g's	--	2240.25	923	Structure acceleration --vertical	50-64	
FR	CEC 4-2-4-001	5 g's	--	--	610	Structure accelerarion --upstream-downstream	50-64	
FT	CEC 4-2-4-001	5 g's	--	--	538	Structure acceleration --transverse	50-64	
SB1	CEC 4-312	100 psia	3+50.0	Varied	923†	Stilling basin wall pressure	65-72	Transducers were replaced and interchanged during tests. All were the same model and range
SB2	CEC 4-312	100 psia	4+02.0	Varied	610†	Stilling basin wall pressure	65-72	
SB3	CEC 4-312	100 psia	4+54.0	Varied	927	Stilling basin wall pressure	65-72	
SB4	CEC 4-312	100 psia	5+06.0	Varied	918	Stilling basin wall pressure	65-72	
SB5	CEC 4-312	100 psia	5+58.0	Varied	923	Stilling basin wall pressure	65-72	

* All strain gage transducers, except piezoelectric, at 3K, 4AK.

** See Plate 1.

† Cable length was changed during course of tests.

Table 2

Center Sluice Prototype Pressures, Velocities, and Cavitation Indices

Gate Opening ft	Item*	Transducer Station 6	5	4	3	2	1	5A	4A	3A
1.0	V	81.67	84.27	85.88	91.93	97.40	105.86	84.27	85.88	91.93
Q = 900 cfs	K	0.200	0.115	0.111	0.234	0.181	0.159	0.179	0.207	0.181
	H	-4	0	0	20	4	20	-5	-1	3
	M	-10	-18	-18	0	-4	-3	-11	-7	-7
	L	-16	-30	-31	-13	-9	-25	-23	-9	-15
	P/P	10	30	31	33	15	31	29	35	37
2.0	V	103.2	104.5	105.1	105.7	107.7	111.8	104.5	105.1	105.7
Q = 1,750 cfs	K	0.113	0.122	0.162	0.148	0.121	0.137	0.199	0.150	0.137
	H	-3	1	6	8	1	5	11	7	4
	M	-12	-10	-3	-5	-9	-4	3	-5	-7
	L	-20	-23	-17	-14	-18	-14	-17	-19	-14
	P/P	14	17	19	24	15	15	29	18	14
3.0	V	112.6	111.4	110.9	110.6	110.4	110.9	111.4	110.9	110.6
Q = 2,450 cfs	K	0.120	0.113	0.140	0.130	0.141	0.140	0.128	0.145	0.151
	H	2	1	5	8	0	6	2	12	25
	M	-7	-9	-4	-6	-4	-4	-6	-3	-2
	L	-13	-16	-15	-20	-9	-12	-16	-15	-20
	P/P	13	18	19	26	8	14	15	22	38
4.0	V	111.5	109.95	109.38	109.00	108.43	108.25	109.95	109.38	109.00
Q = 3,150 cfs	K	0.087	0.126	0.138	0.161	0.124	0.147	0.137	0.138	0.161
	H	-3	6	**	0.5	2	7	**	**	1
	M	-14	-7	-5	-1	-8	-4	-5	-5	-1
	L	-21	-20	**	-3	-17	-16	**	**	-2
	P/P	17	29	20	3	16	18	15	21	2
5.0	V	112.11	109.81	108.85	108.23	106.99	105.93	109.81	108.85	108.23
Q = 3,780 cfs	K	0.116	0.111	0.140	0.130	0.128	0.147	0.100	0.145	Cell out
	H	17	20	23	32	9	6	**	15	
	M	-8	-10	-5	-7	-8	-5	-12	-4	
	L	-22	-25	-24	-30	-22	-13	**	-13	
	P/P	35	41	45	50	32	15		21	
6.0	V	114.65	111.94	110.84	110.02	108.70	107.02	111.94	110.84	110.02
Q = 4,500 cfs	K	0.126	0.112	0.140	0.121	0.129	0.150	0.137	0.145	--
	H	3	1	9	4	2	6	7	10	
	M	-5	-9	-4	-8	-7	-4	-4	-3	Cell out
	L	-15	-17	-13	-16	-16	-12	-14	-12	
	P/P	15	16	16	15	16	13	17	18	
7.0	V	116.07	112.92	111.71	110.87	109.02	107.00	112.92	111.71	110.87
Q = 5,200 cfs	K	0.103	0.104	0.158	0.135	0.128	0.150	0.206	0.158	--
	H	-6	**	**	**	2	5	**	**	Cell out
	M	-9	-10	0	-5	-7	-4	10	0	
	L	-19	**	**	**	-15	-14	**	**	
	P/P	17	25	16	17	17	17	32	24	
8.0	V	118.51	115.23	113.90	113.04	111.11	108.89	115.23	113.90	113.04
Q = 6,000 cfs	K	0.081	0.076	0.138	0.112	0.118	0.145	0.057	0.150	--
	H	-3	**	**	**	2	2	**	**	Cell out
	M	-13	-15	-3	-8	-8	-4	-19	-2	
	L	-25	**	**	**	-16	-13	**	**	
	P/P	28	23	16	23	14	15	25	22	

(Continued)

* V = average velocity, K = cavitation index, H = highest instantaneous pressure, M = mean pressure, L = lowest instantaneous pressure, and P/P = greatest peak-peak pressure.

** Scale factor such that peaks were not distinguishable on oscillograph records.

Table 2 (Concluded)

Gate Opening ft	Item	Transducer Station								
		6	5	4	3	2	1	5A	4A	3A
9.0	V	120.73	117.29	115.91	114.99	112.94	110.54	117.29	115.91	114.99
Q = 6,850 cfs	K	0.109	0.111	0.142	0.081	0.125	0.141	0.120	0.147	0.111
	H	2	-1	5	-6	2	5	4	11	7
	M	-6	-7	-1	-14	-6	-4	-5	0	-8
	L	-15	-15	-11	-26	-15	-13	-17	-10	-19
	P/P	13	14	14	20	17	16	13	19	20
10.0	V	122.46	118.90	117.41	116.53	114.41	111.92	118.90	117.47	116.53
Q = 7,700 cfs	K	0.115	0.103	0.129	0.112	0.117	0.137	0.113	0.129	0.131
	H	4	1	10	3	2	5	8	10	16
	M	-4	-8	-3	-7	-7	-4	-6	-3	-3
	L	-14	-18	-12	-18	-16	-13	-16	-12	-12
	P/P	14	18	18	18	13	14	20	19	23
11.0	V	125.04	121.42	119.97	118.85	116.83	114.22	121.42	119.97	118.85
Q = 8,700 cfs	K	0.102	0.104	0.133	0.113	0.117	0.132	0.112	0.133	0.090
	H	2	1	10	6	4	4	8	11	3
	M	-6	-7	-1	-6	-6	-4	-5	-1	-11
	L	-17	-20	-12	-28	-16	-12	-22	-10	-24
	P/P	15	16	14	26	15	13	23	20	22
12.0	V	126.27	122.51	120.99	119.86	117.75	115.04	122.51	120.99	119.86
Q = 9,700 cfs	K	0.108	0.102	0.117	0.102	0.115	0.130	0.119	0.135	0.106
	H	3	9	6	0	4	6	6	13	3
	M	-4	-7	-4	-8	-6	-4	-3	0	-7
	L	-12	-19	-12	-15	-15	-14	-14	-9	-21
	P/P	15	28	15	16	17	14	26	20	23
13.0	V	126.89	123.02	121.15	120.32	118.10	115.23	123.02	121.15	120.32
Q = 10,820 cfs	K	0.107	0.109	0.117	0.097	0.109	0.129	0.113	0.139	--
	H	2	4	-3	1	4	6	7	12	
	M	-4	-5	-4	-9	-7	-4	-4	1	Calib. error
	L	-12	-12	-13	-20	-17	-13	-15	-11	
	P/P	10	14	11	17	17	15	19	19	
14.0	V	130.08	126.26	124.74	123.58	121.42	118.58	126.26	124.74	123.58
Q = 12,000 cfs	K	0.094	0.088	0.111	0.087	0.099	0.127	0.104	0.123	0.104
	H	2	0	6	16	4	7	4	11	2
	M	-6	-9	-4	-10	-8	-3	-5	-1	-6
	L	-14	-18	-14	-25	-25	-14	-15	-9	-17
	P/P	13	16	21	35	23	16	16	18	16
15.0	V	129.24	125.21	123.58	122.36	120.04	117.01	125.21	123.58	122.36
Q = 13,550 cfs	K	0.091	0.080	0.113	0.093	0.097	0.130	0.109	0.117	0.093
	H	0	1	6	15	1	10	6	9	1
	M	-7	-10	-4	-9	-9	-3	-4	-3	-9
	L	-15	-21	-16	-31	-20	-13	-12	-13	-19
	P/P	14	19	40	39	17	18	15	17	15
16.0	V	129.64	125.44	123.83	122.58	120.21	117.06	125.44	123.83	122.58
Q = 15,200 cfs	K	0.091	0.087	0.108	0.087	0.097	0.130	0.093	0.116	0.093
	H	1	1	9	21	2	7	5	7	0
	M	-7	-10	-5	-10	-9	-3	-8	-3	-9
	L	-14	-22	-16	-21	-21	-14	-15	-11	-19
	P/P	11	20	21	38	22	18	16	18	15
16.5	V	127.68	123.38	121.65	120.36	117.86	114.55	123.38	121.65	120.36
Q = 16,100 cfs	K	0.098	0.092	0.121	0.088	0.101	0.136	0.113	0.121	0.096
	H	1	1	7	5	2	8	6	9	1
	M	-6	-9	-3	-11	-9	-3	-4	-3	-9
	L	-13	-18	-14	-22	-20	-16	-12	-15	-20
	P/P	10	18	18	27	18	19	15	19	16
16.5 to 16.9	H	0	5	9	10	1	12	9	12	1
	M	-6	-8	-1	-8	-9	-3	-3	-1	-9
	L	-13	-21	-12	-22	-22	-14	-18	-10	-21
	P/P	11	20	16	26	18	21	18	15	17

Table 3

Center Sluice Prototype Gate Vibration, August 1974

Record No.	Gate Opening ft	Item	Gate Tangential	Gate Radial	Gate Transverse	Gallery Floor Vertical	Gallery Floor Upstream/ Downstream	Gallery Floor Transverse
50A	1	Graph						
		Freq, Hz	--	--	--	--	--	--
		Accel, g's	--	--	--	--	--	--
		Displ, μ ft*	--	--	--	--	--	--
		Sample						
		Max, g's	+0.033	+0.022	+0.016	+0.007	+0.007	+0.005
		Min, g's	-0.031	-0.023	-0.015	-0.007	-0.005	-0.006
		RMS, g's	0.023	0.006	0.005	0.002	0.002	0.002
		FFT						
		Max a, g's	0.0029	0.0018	0.0030	0.0017	0.0010	0.0008
		Freq, Hz	263	155	180	180	180	60
		Avg						
		Max a, g's	0.0017	0.0006	0.0008	0.0004	0.0002	0.0002
		Freq, Hz	262	46	60	59	59	59
51	5	Graph						
		Freq, Hz	--	--	--	--	--	--
		Accel, g's	--	--	--	--	--	--
		Displ, μ ft	--	--	--	--	--	--
		Sample						
		Max, g's	+0.081	+0.038	+0.024	+0.007	+0.006	+0.005
		Min, g's	-0.087	-0.051	-0.023	-0.007	-0.006	-0.005
		RMS, g's	0.025	0.011	0.006	0.002	0.002	0.002
		FFT						
		Max, g's	0.0109	0.0023	0.0031	0.0017	0.0011	0.0009
		Freq, Hz	259	69	180	180	180	60
		Avg						
		Max a, g's	0.0050	0.0011	0.0008	0.0004	0.0002	0.0002
		Freq, Hz	259	26	60	59	59	59
52	7	Graph						
		Freq, Hz	260	60	60	--	--	--
		Accel, g's	0.047	0.066	0.031	--	--	--
		Displ, μ ft	0.5	19.0	6.9	--	--	--
		Sample						
		Max, g's	+0.291	+0.505	+0.109	+0.014	+0.015	+0.012
		Min, g's	-0.295	-0.517	-0.087	-0.011	-0.014	-0.014
		RMS, g's	0.090	0.168	0.027	0.004	0.004	0.004
		FFT						
		Max a, g's	0.0315	0.1274	0.0115	0.0018	0.0025	0.0023
		Freq, Hz	258	74	40	74	74	74
		Avg						
		Max a, g's	0.0135	0.0271	0.0043	0.0004	0.0005	0.0004
		Freq, Hz	254	73	39	59	128	128
53	10	Graph						
		Freq, Hz	260	60	60	--	--	--
		Accel, g's	0.124	0.132	0.041	--	--	--
		Displ, μ ft	1.5	30.0	9.3	--	--	--
		Sample						
		Max, g's	+0.076	+0.105	+0.026	+0.008	+0.006	+0.006
		Min, g's	-0.068	-0.134	-0.023	-0.006	-0.006	-0.006
		RMS, g's	0.017	0.023	0.007	0.002	0.002	0.002
		FFT						
		Max a, g's	0.0060	0.0057	0.0030	0.0017	0.0010	0.0008
		Freq, Hz	27	35	60	60	180	60
		Avg						
		Max a, g's	0.0025	0.0029	0.0008	0.0004	0.0002	0.0002
		Freq, Hz	26	33	65	59	59	59

(Continued)

Note: Maximum values at 60± and 180± Hz probably are electrical circuit noise. See FFT plots for other maximum values. Accelerometer natural frequency less than 100 Hz. Values at frequencies above that are rapidly damped at increasing severity. Pressure transducer natural frequency is well above 500 Hz.

Graph = oscillogram, from which next 3 items were obtained visually.
Freq, Hz = significant frequency of oscillation used.
Accel, g's = full width of acceleration trace envelope (peak-to-peak).
Displ, μ ft = peak-to-peak sinusoidal displacement = acceleration/$(2\pi \text{ frequency})^2$.
Sample = digitized sample, about 4 sec at 1000 per sec (from magnetic tape).
Max, g's = greatest instantaneous acceleration in (+) direction.
Min, g's = greatest instantaneous acceleration in (-) direction.
RMS, g's = root-mean-square of fluctuations.
FFT = Fast Fourier Transform indication of spectrum (2024 steps) (from sample).
Max a, g's = values of maximum "a" in: $g = a_1 \sin w_1 t + a_2 \sin w_2 t + \ldots$
Freq, Hz = frequency step corresponding to maximum "a."
Avg = eight-step running average of FFT values (from sample).
Max a, g's = values of maximum "a" (as above).
Freq, Hz = frequency corresponding to maximum "a."
μ ft = 0.000001 ft.

* Data omitted where recorded measurements were insignificant.

Table 3 (Concluded)

Record No.	Gate Opening ft	Item	Gate: Tangential	Gate: Radial	Gate: Transverse	Gallery Floor: Vertical	Gallery Floor: Upstream/ Downstream	Gallery Floor: Transverse
55	11	Graph						
		Freq, Hz	--	--	--	--	--	--
		Accel, g's	--	--	--	--	--	--
		Displ, µ ft*	--	--	--	--	--	--
54	12	Graph						
		Freq, Hz	260	40	60	--	--	--
		Accel, g's	0.20	0.19	0.10	--	--	--
		Displ, µ ft	2.4	100.0	52.0	--	--	--
		Sample						
		Max, g's	+0.104	+0.186	+0.049	+0.008	+0.007	+0.007
		Min, g's	-0.122	-0.172	-0.049	-0.007	-0.007	-0.007
		RMS, g's	0.029	0.042	0.015	0.003	0.002	0.002
		FFT						
		Max a, g's	0.0078	0.0151	0.0046	0.0018	0.0011	0.0008
		Freq, Hz	258	40	38	180	180	60
		Avg						
		Max a, g's	0.0043	0.0061	0.0027	0.0004	0.0002	0.0002
		Freq, Hz	257	43	37	59	59	59
56	13	Graph						
		Freq, Hz	--	--	--	--	--	--
		Accel, g's	--	--	--	--	--	--
		Displ, µ ft	--	--	--	--	--	--
57	14	Graph						
		Freq, Hz	250	60	60	60	60	60
		Accel, g's	0.80	0.85	0.31	--	--	--
		Displ, µ ft	14.0	190.0	78.0	--	--	--
		Sample						
		Max, g's	+0.224	+0.339	+0.113	+0.009	+0.007	+0.008
		Min, g's	-0.246	-0.374	-0.099	-0.008	-0.008	-0.007
		RMS, g's	0.055	0.086	0.026	0.003	0.002	0.002
		FFT						
		Max a, g's	0.0137	0.0196	0.0080	0.0018	0.0012	0.0008
		Freq, Hz	264	50	42	180	180	60
		Avg						
		Max a, g's	0.0091	0.0123	0.0053	0.0004	0.0002	0.0002
		Freq, Hz	264	50	42	59	59	59
58	15	Graph						
		Freq, Hz	250	60	150	60	60	60
		Accel, g's	0.43	0.87	0.19	0.01	0.01	0.01
		Displ, µ ft	5.6	200.0	7.0	2.2	2.4	2.1
		Sample						
		Max, g's	+0.263	+0.333	+0.092	+0.008	+0.006	+0.007
		Min, g's	-0.327	-0.404	-0.093	-0.008	-0.007	-0.007
		RMS, g's	0.067	0.098	0.023	0.002	0.002	0.002
		FFT						
		Max a, g's	0.0189	0.0250	0.0045	0.0016	0.0009	0.0009
		Freq, Hz	260	56	44	180	180	60
		Avg						
		Max a, g's	0.0130	0.0142	0.0023	0.0004	0.0002	0.0002
		Freq, Hz	259	54	30	60	59	59
59	15.5	Graph						
		Freq, Hz	260	60	60	60	60	60
		Accel, g's	0.34	0.50	0.13	0.01	0.01	0.01
		Displ, µ ft	4.1	115.0	31.6	3.2	3.0	2.6
		Sample						
		Max, g's	+0.198	+0.402	+0.089	+0.008	+0.006	+0.006
		Min, g's	-0.184	-0.352	-0.086	-0.008	-0.007	-0.007
		RMS, g's	0.053	0.093	0.023	0.002	0.002	0.002
		FFT						
		Max, g's	0.0136	0.0239	0.0068	0.0018	0.0011	0.0008
		Freq, Hz	261	56	49	180	180	155
		Avg						
		Max a, g's	0.0073	0.0118	0.0025	0.0004	0.0002	0.0002
		Freq, Hz	262	56	57	59	59	59

* Data omitted where recorded measurements were insignificant.

Table 4

Stilling Basin Wall Pressures, Feet of Water

	Transducer Location					Equivalent Tailwater*	Comments
	PC-1	PC-2	PC-3	PC-4	PC-5		
Mean	23	33	52	33	36	2119	Test No. 65
High	59	53	58	41	40		Q = 20,000 cfs
Low	-18	0	36	28	32		Transducer el 2083
Peak to peak	52	27	10	8	5		Entering $V^2/2g$ = 293 ft
Ratio**	0.18	0.09	0.03	0.03	0.02		
Mean	12	26	50	29	36	2119	Test No. 66
High	60	55	69	42	42		Q = 29,000 cfs
Low	-27	-5	30	17	29		Transducer el 2083
Peak to peak	69	38	20	8	6		Entering $V^2/2g$ = 343 ft
Ratio	0.20	0.11	0.06	0.02	0.02		
Mean	-4	24	48	35	39	2122	Test No. 67
High	67	81	85	53	47		Q = 37,000 cfs
Low	-31	-11	15	21	28		Transducer el 2083
Peak to peak	91	63	41	19	8		Entering $V^2/2g$ = 372 ft
Ratio	0.24	0.17	0.11	0.05	0.02		
Mean	Transducer out	26	50	32	41	2124	Test No. 68
High		72	77	44	48		Q = 47,000 cfs†
Low		-5	28	20	31		Transducer el 2083
Peak to peak		62	41	17	10		Entering $V^2/2g$ = 396 ft**
Ratio		0.16	0.10	0.05	0.02		
	PC-6	PC-7	PC-8	PC-9	PC-10		
Mean	-7	7	12	15	No transducer	2119	Test No. 69
High	14	14	19	19			Q = 20,000 cfs
Low	0	2	4	8			Transducer el 2110
Peak to peak	7	8	14	8			Entering $V^2/2g$ = 293 ft
Mean	0	6	19	9	No transducer	2119	Test No. 70
High	6	16	32	16			Q = 29,000 cfs
Low	-3	-3	9	-3			Transducer el 2110
Peak to peak	8	12	17	21			Entering $V^2/2g$ = 343 ft
	PC-11	PC-12	PC-13	PC-14	PC-15		
Mean	3	2	-2	1	No transducer	2119	Test No. 71
High	5	6	3	4			Q = 20,000 cfs
Low	0	-2	-4	-2			Transducer el 2128
Peak to peak	5	6	7	6			Entering $V^2/2g$ = 293 ft
Mean	1	0	-3	-2	No transducer	2119	Test No. 72
High	4	4	2	6			Q = 29,000 cfs
Low	-1	-4	-7	-4			Transducer el 2128
Peak to peak	5	6	8	11			Entering $V^2/2g$ = 343 ft

* Equivalent tailwater calculated using mean pressure of transducer farthest downstream.

** $(Pk-PK)/V^2/2g)$, significant at transducers PC-1 through PC-5 only.

† Approximate value--test stopped due to high flow damage.

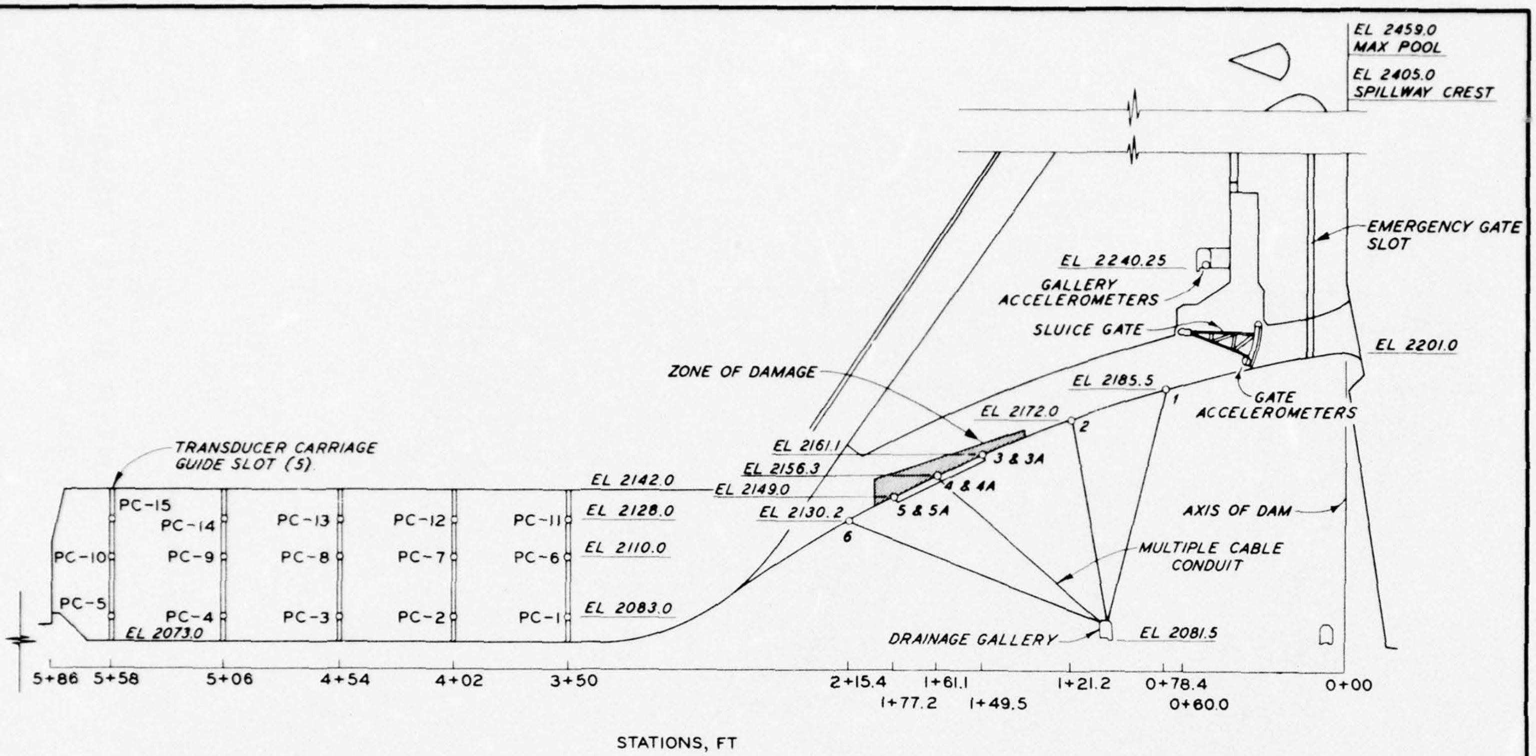
Table 5

Stilling Basin Wall Pressures in Feet of Water

Transducer Position	El msl	M--20,000 cfs* P--20,000 cfs						M--30,000 cfs* P--29,000 cfs						M--40,000 cfs* P--37,000 cfs					
		Instantaneous						Instantaneous						Instantaneous					
		Maximum		Minimum		Mean		Maximum		Minimum		Mean		Maximum		Minimum		Mean	
		M	P	M	P	M	P	M	P	M	P	M	P	M	P	M	P	M	P
PC-1	2083	41	59	2	-18	23	23	60	60	-6	-27	17	12	65	67	-29	-33	18	-4
PC-2		49	53	-3	0	33	33	58	55	-4	-5	29	26	71	81	-5	-11	28	24
PC-3		50	58	21	36	38	52	60	69	13	30	37	50	62	85	7	15	38	48
PC-4		47	41	35	28	43	34	54	42	27	17	43	29	58	53	23	21	44	35
PC-5		43	40	39	32	41	36	46	42	35	29	42	36	50	47	32	28	42	39
PC-6	2110	16	14	1	0	8	7	11	6	-4	-3	4	0	13		-2		1	
PC-7		X	14	X	2	X	7	X	16	X	-3	X	6	X		X		X	
PC-8		23	19	7	4	16	12	30	32	2	9	16	19	36		0		14	
PC-9		20	19	10	8	14	15	26	16	7	-3	16	9	26		0		16	
PC-10		24	X	15	X	20	X	27	X	15	X	22	X	31		1		23	
PC-11	2128	-	5	-	0	-	3	-	4	-	-1	-	1	-		-		-	
PC-12		2	6	-	-2	-	2	3	3	-	-4	-	0	3		-		-	
PC-13		6	3	-	-4	-	-2	11	2	-	-7	-	-3	7		-		-	
PC-14		7	4	-	-2	-	1	7	6	-	-4	2	-2	13		-		3	
PC-15		3	X	-	X	-	X	7	X	-	X	1	X	10		-		2	
Tailwater el						2126.7	2119.0					2128.5	2119.0					2130.2	2122.0

Note: All pressures are in feet of water (gage) at transducers.
- = Dry
X = instrument malfunction
M = model data
P = prototype data
Blanks indicate these tests were not conducted due to earlier damage.

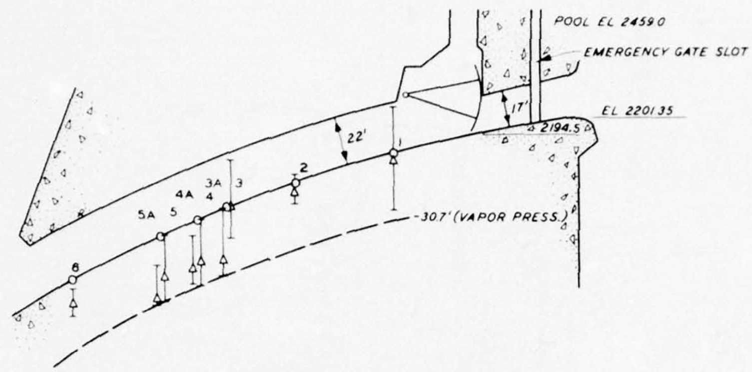
* Model study data obtained with 10,000-cfs powerhouse discharge in addition to discharge shown above.



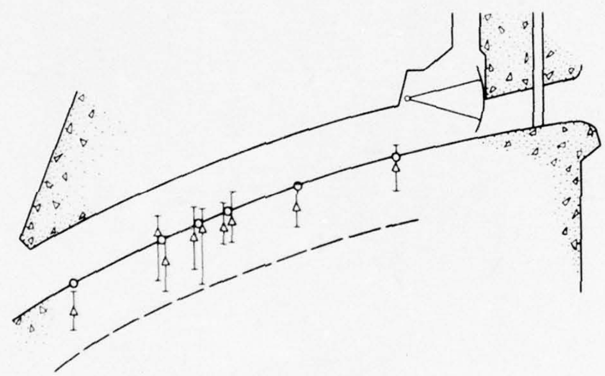
PC-1 THROUGH PC-15 DENOTE PRESSURE CELL LOCATIONS ON STILLING BASIN WALL

PRESSURE SENSORS 1-6 ARE LOCATED ALONG CENTER LINE OF SLUICE INVERT AND 3A, 4A, AND 5A NEAR THE INTERSECTION OF INVERT AND RIGHT WALL, ALL ON INVERT.

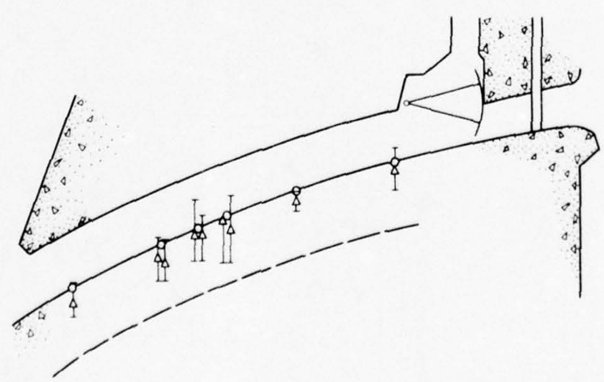
SECTION THROUGH MONO 29 (CENTER SLUICE)
LIBBY DAM PROTOTYPE TEST - 1974



1.0-FT OPENING



2.0-FT OPENING



3.0-FT OPENING

LIBBY DAM

CENTER SLUICE PRESSURES

1.0, 2.0, AND 3.0-FT GATE OPENINGS

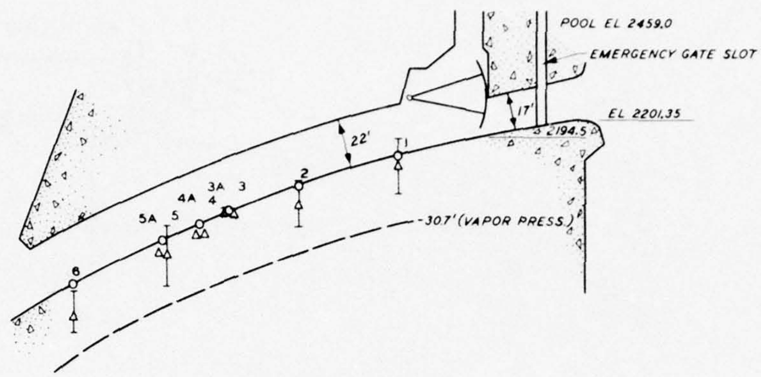
SCALE IN FEET

50 0 50 100

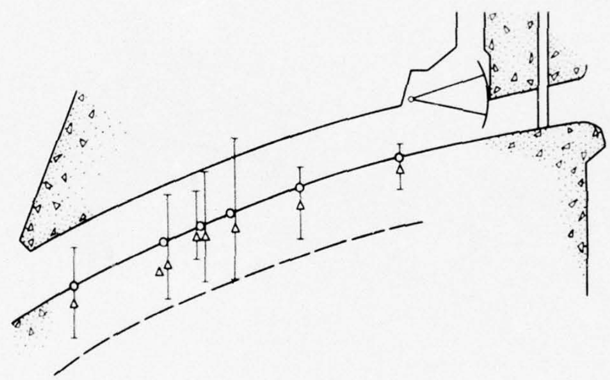
LEGEND

- MAX PRESSURE
- TRANSDUCER (ZERO)
- AVG PRESSURE
- MIN PRESSURE

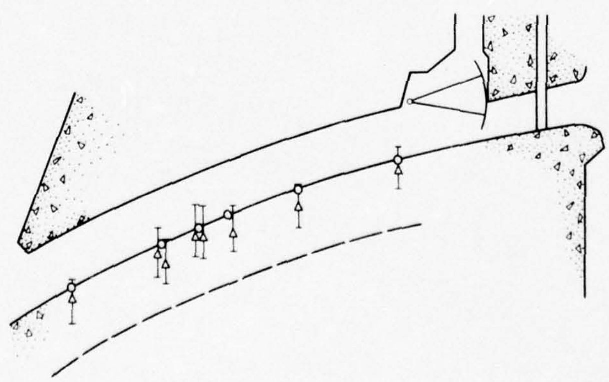
PLATE 2



4.0-FT OPENING



5.0-FT OPENING



6.0-FT OPENING

LEGEND

- MAX PRESSURE
- TRANSDUCER (ZERO)
- AVG PRESSURE
- MIN PRESSURE

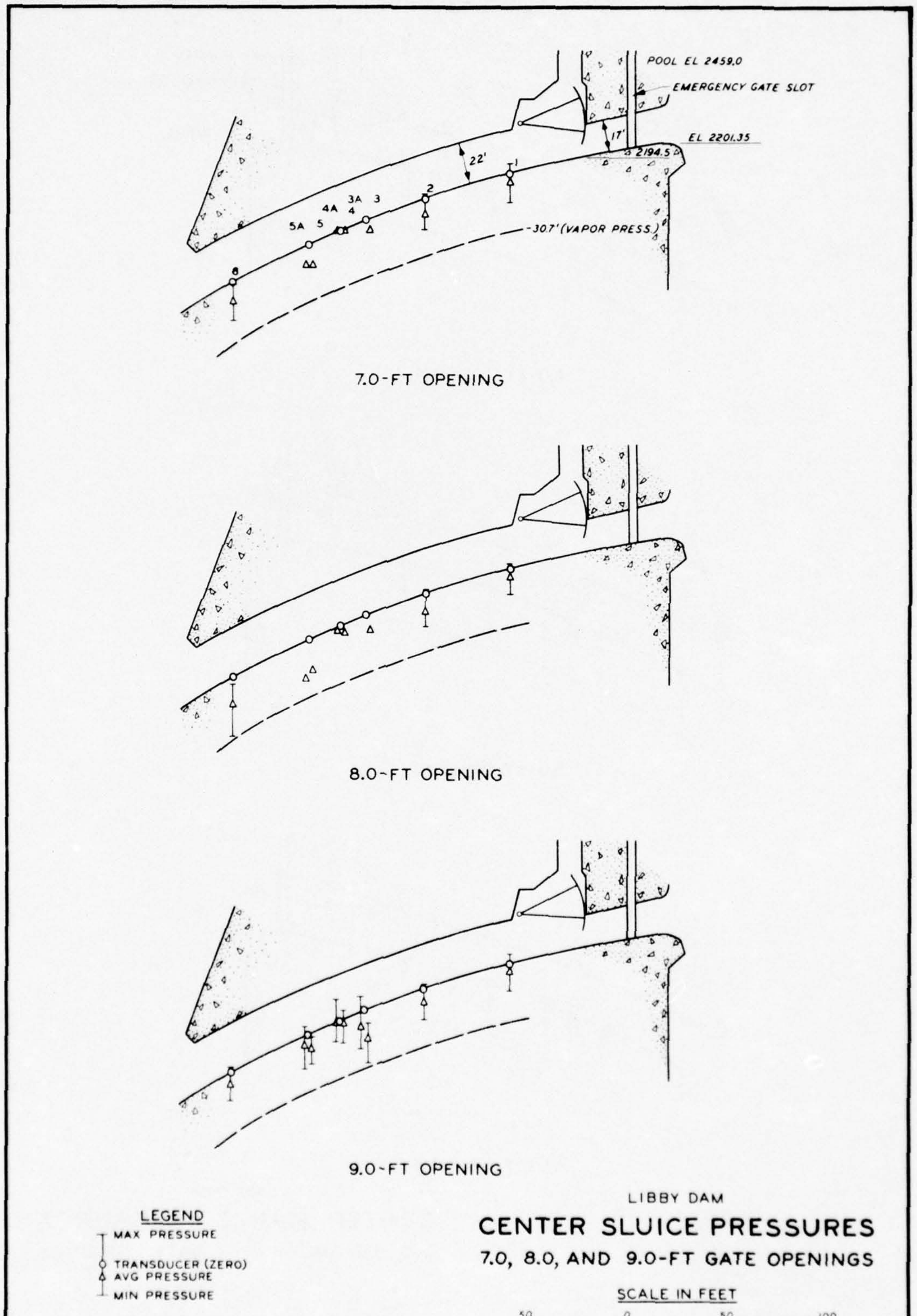
LIBBY DAM

CENTER SLUICE PRESSURES

4.0, 5.0, AND 6.0-FT GATE OPENINGS

SCALE IN FEET

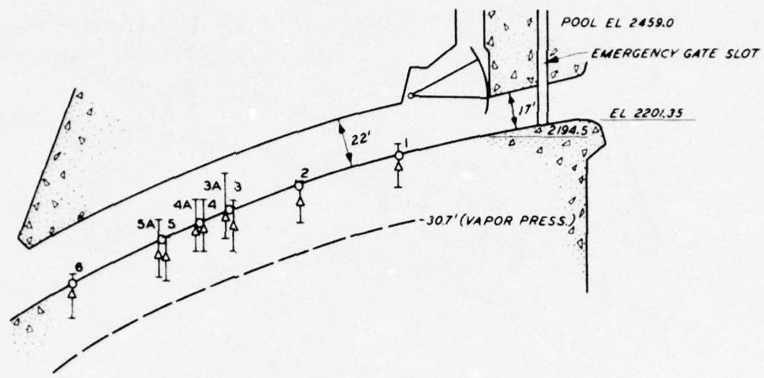
50 0 50 100



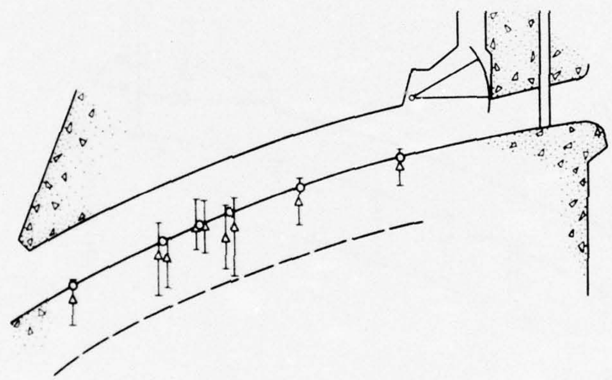
LIBBY DAM

CENTER SLUICE PRESSURES

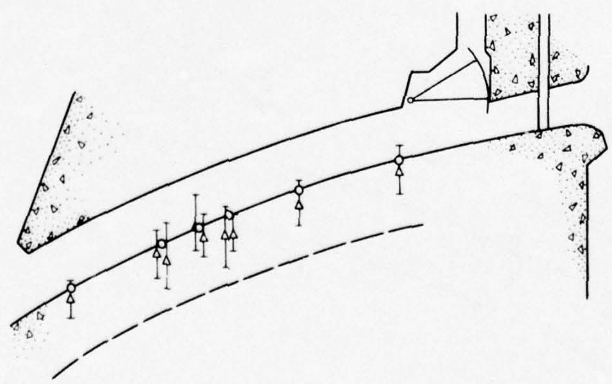
7.0, 8.0, AND 9.0-FT GATE OPENINGS



10.0-FT OPENING



11.0-FT OPENING



12.0-FT OPENING

LEGEND

- MAX PRESSURE
- TRANSDUCER (ZERO)
- AVG PRESSURE
- MIN PRESSURE

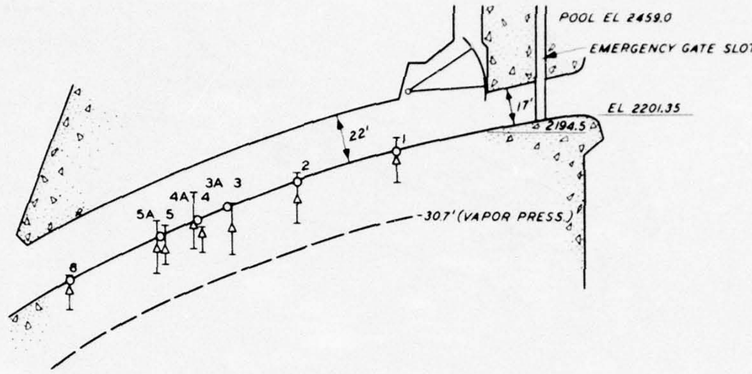
LIBBY DAM

CENTER SLUICE PRESSURES

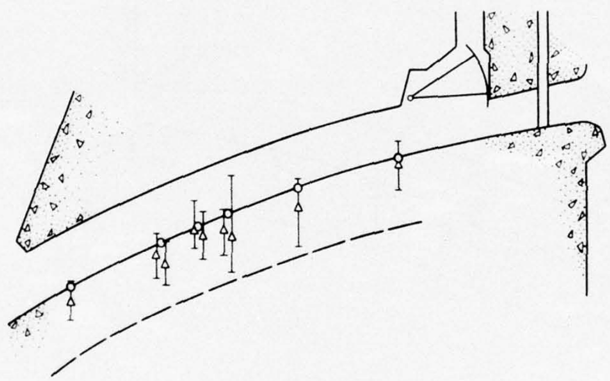
10.0, 11.0, AND 12.0-FT GATE OPENINGS

SCALE IN FEET

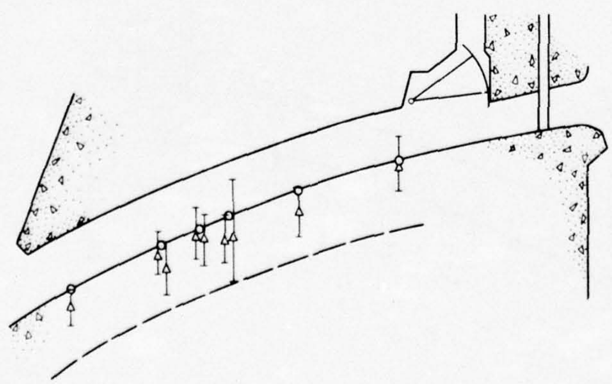
50 0 50 100



13.0-FT OPENING



14.0-FT OPENING



15.0-FT OPENING

LEGEND

MAX PRESSURE
TRANSDUCER (ZERO)
AVG PRESSURE
MIN PRESSURE

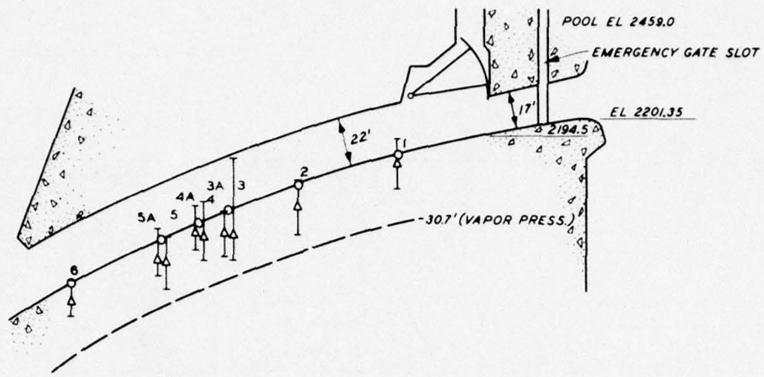
LIBBY DAM

CENTER SLUICE PRESSURES

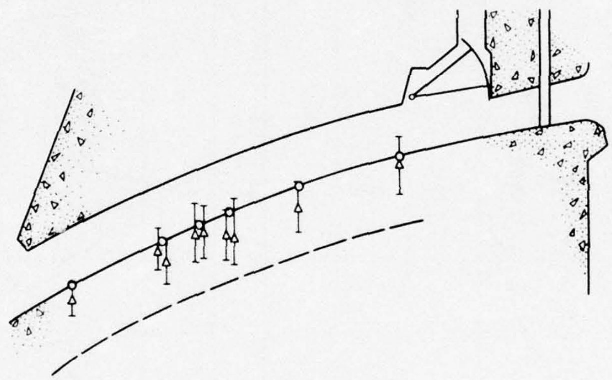
13.0, 14.0, AND 15.0-FT GATE OPENINGS

SCALE IN FEET

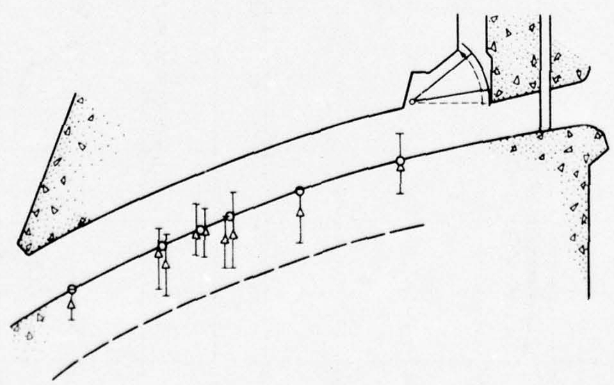
50 0 50 100



16.0-FT OPENING



16.5-FT OPENING



16.5 → 16.9-FT OPENING

LEGEND

MAX PRESSURE

TRANSDUCER (ZERO)
AVG PRESSURE

MIN PRESSURE

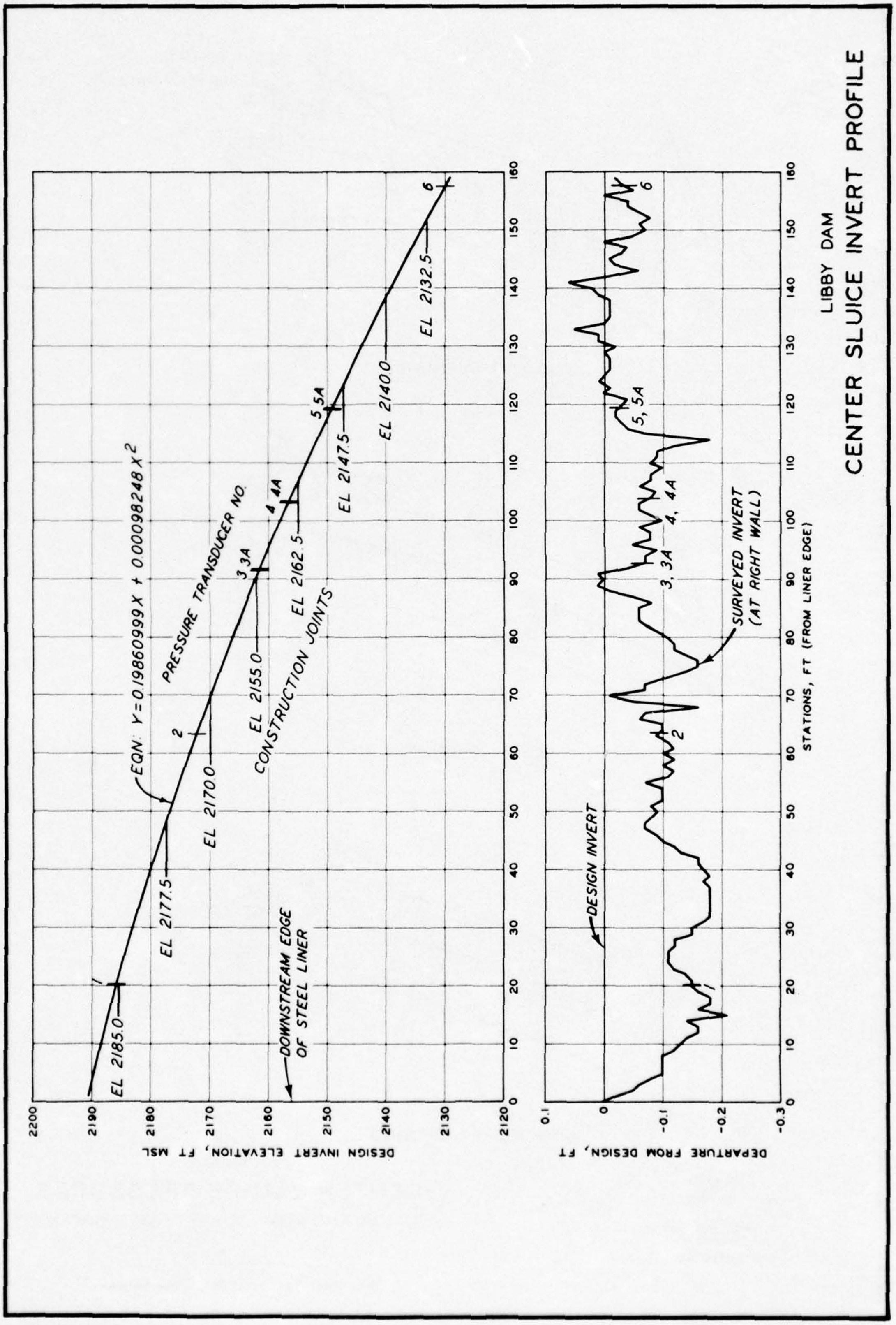
LIBBY DAM

CENTER SLUICE PRESSURES

16.0, 16.5, AND 16.5 → 16.9-FT GATE OPENINGS

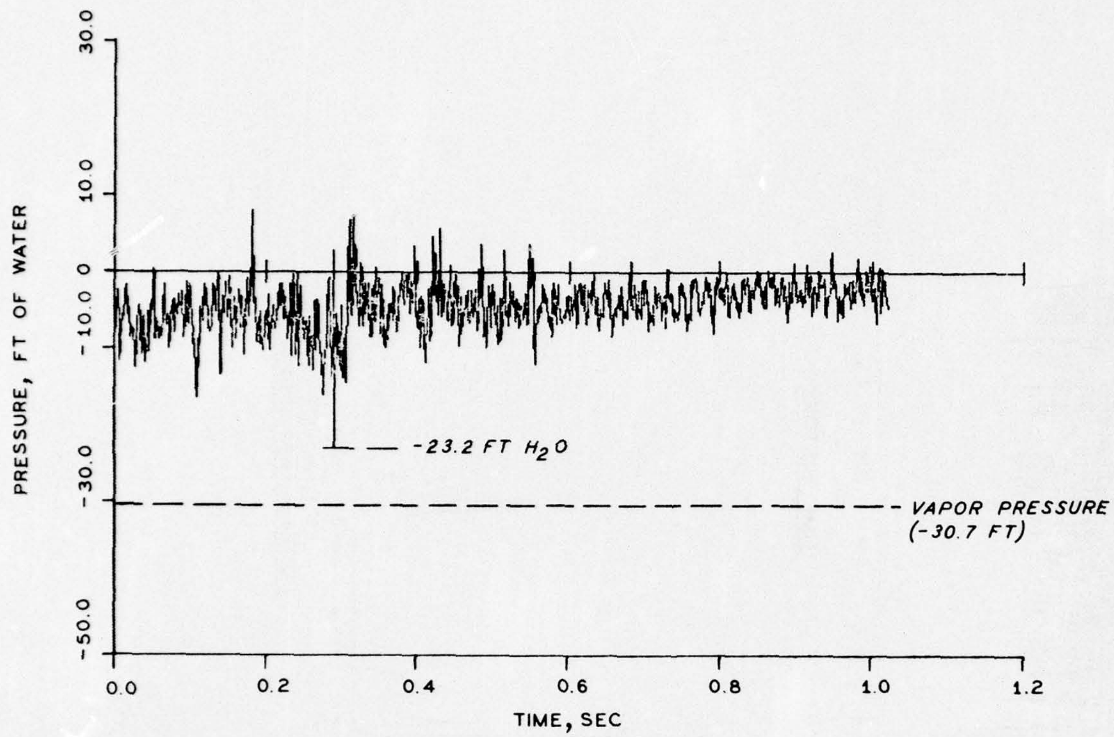
SCALE IN FEET

50 0 50 100



LIBBY DAM

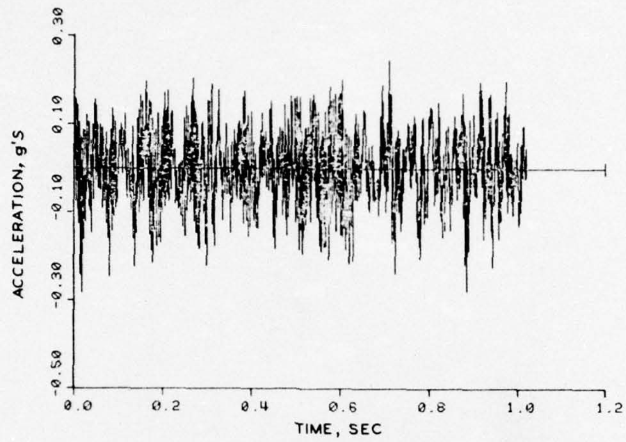
CENTER SLUICE INVERT PROFILE



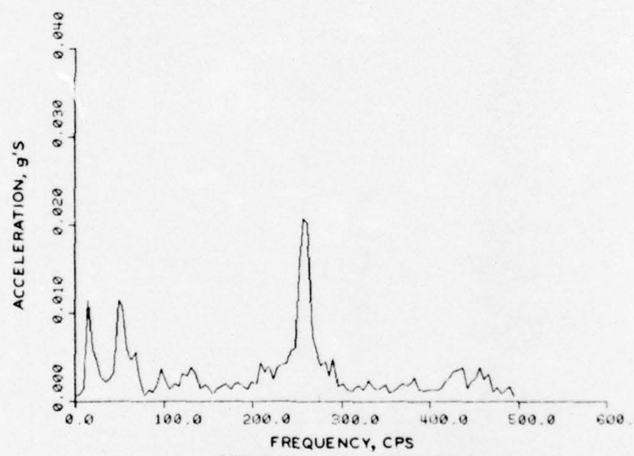
TIME HISTORY

GATE OPENING 5 FT.

CENTER SLUICE PRESSURES
PRESSURE TRANSDUCER 3
DISCHARGE 3800 CFS



TIME HISTORY



FOURIER TRANSFORM

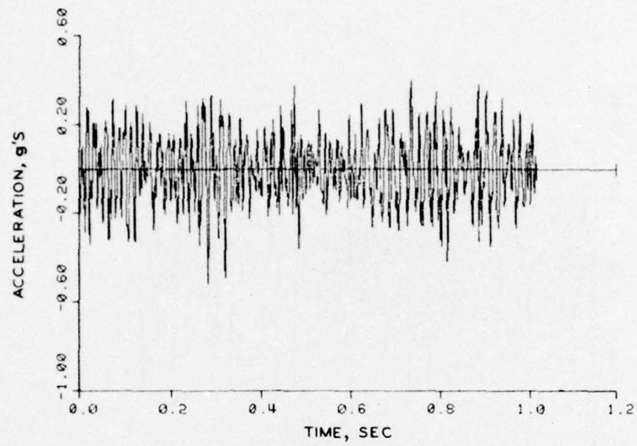
GATE OPENING 16 FT.

CENTER SLUICE ACCELERATIONS

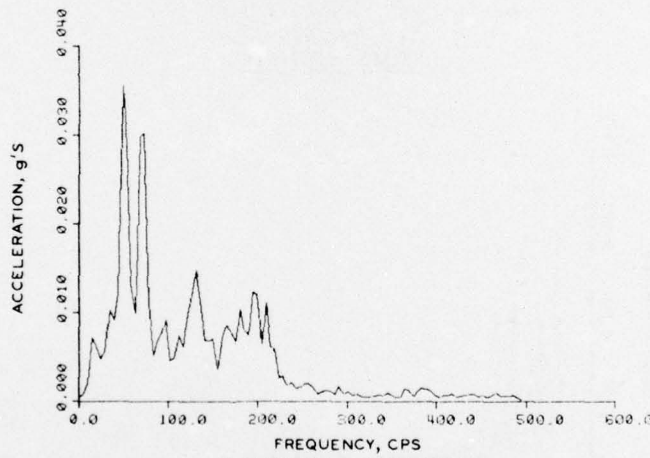
GATE ACCELERATION

DIRECTION TANGENTIAL

DISCHARGE 15,100 CFS



TIME HISTORY



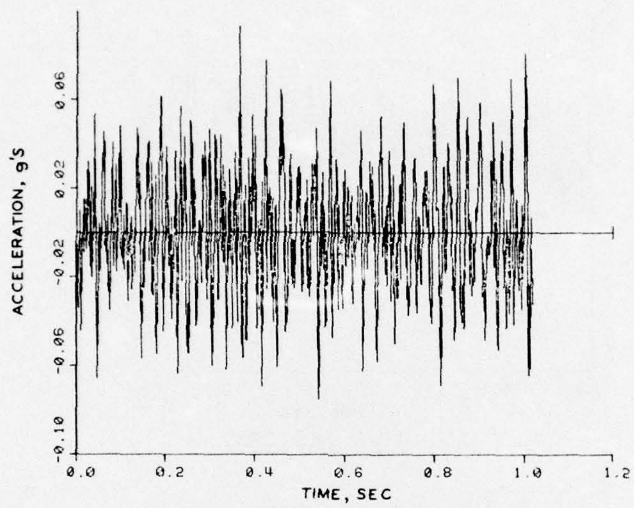
FOURIER TRANSFORM

GATE OPENING 16 FT.

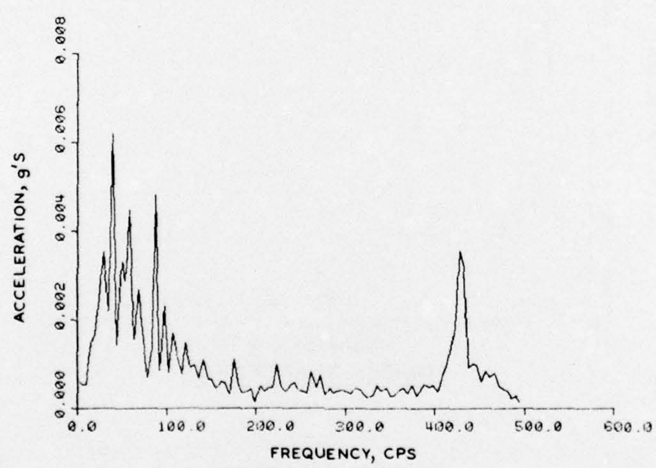
CENTER SLUICE ACCELERATIONS

GATE ACCELERATION
DIRECTION RADIAL

DISCHARGE 15,100 CFS



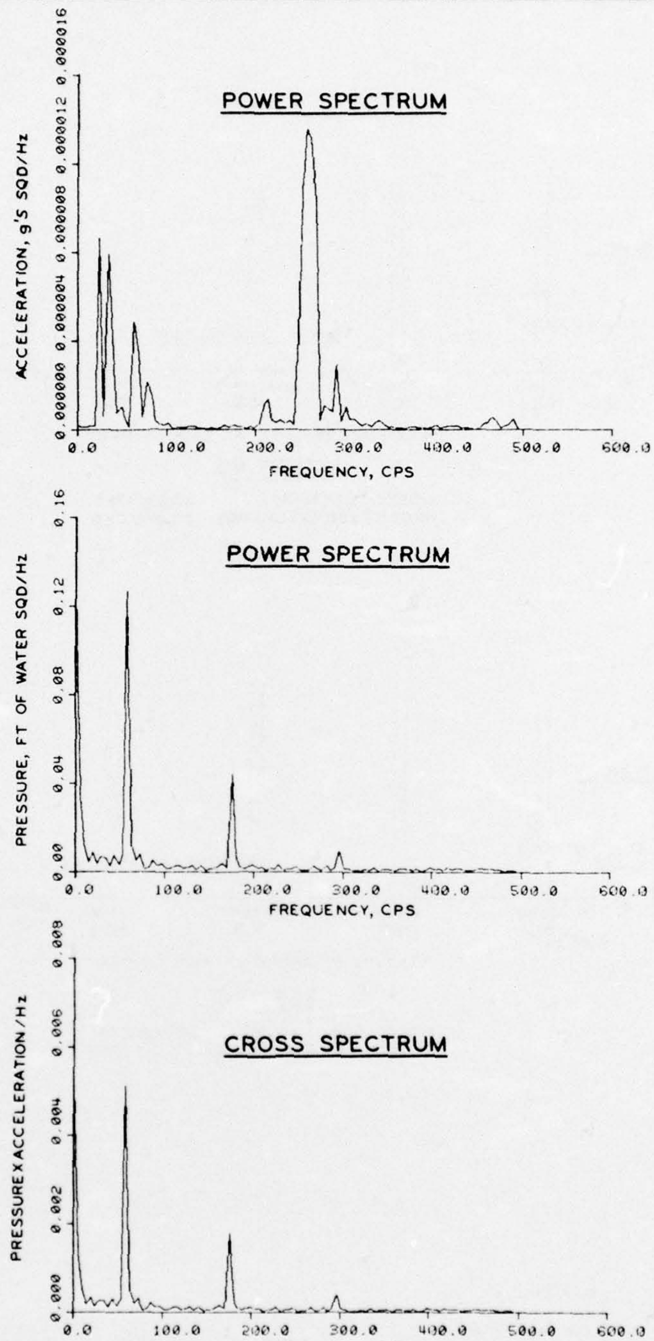
TIME HISTORY



FOURIER TRANSFORM

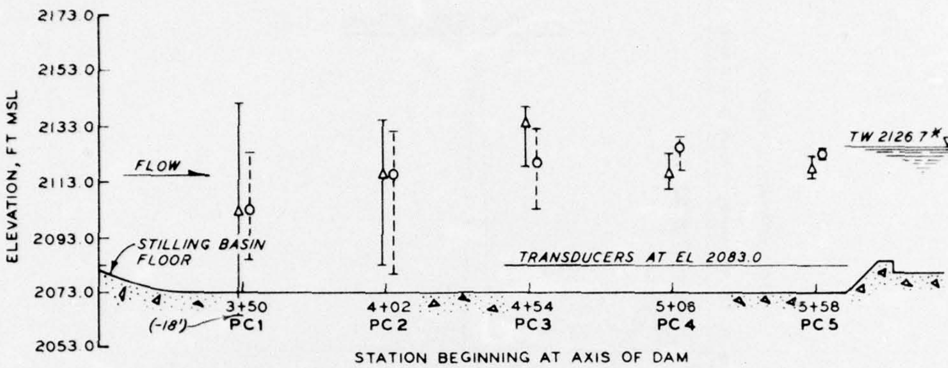
GATE OPENING 16 FT.

CENTER SLUICE ACCELERATIONS
GATE ACCELERATION
DIRECTION TRANSVERSE
DISCHARGE 15,100 CFS



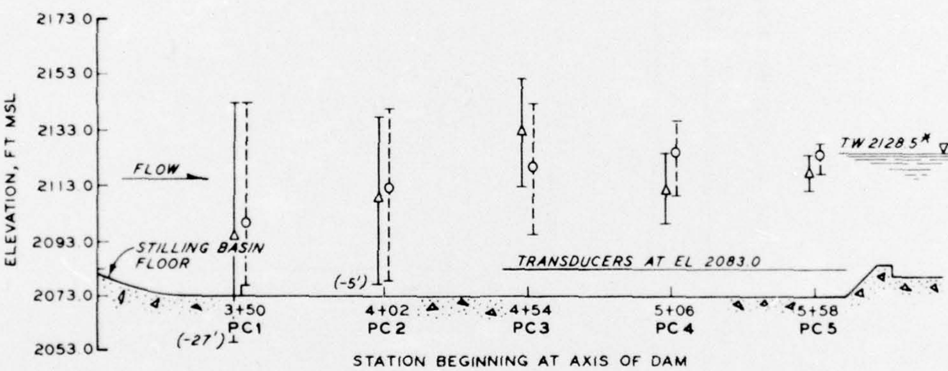
GATE OPENING 10 FT

CENTER SLUICE
PRESSURES AND ACCELERATIONS
PRESSURE TRANSDUCER 5 AND
TANGENTIAL ACCELERATION
DISCHARGE 7700 CFS



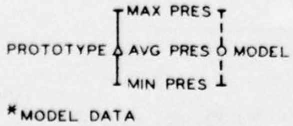
TEST 65

MODEL DISCHARGE 20,000 CFS
PROTOTYPE DISCHARGE 20,000 CFS



TEST 66

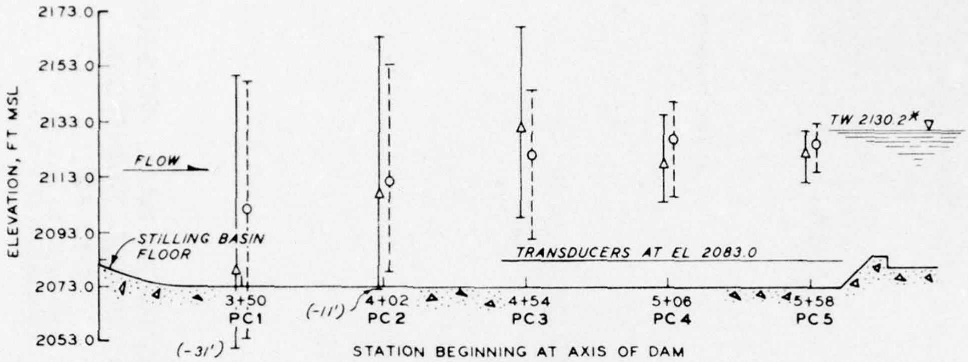
MODEL DISCHARGE 30,000 CFS
PROTOTYPE DISCHARGE 29,000 CFS



*MODEL DATA

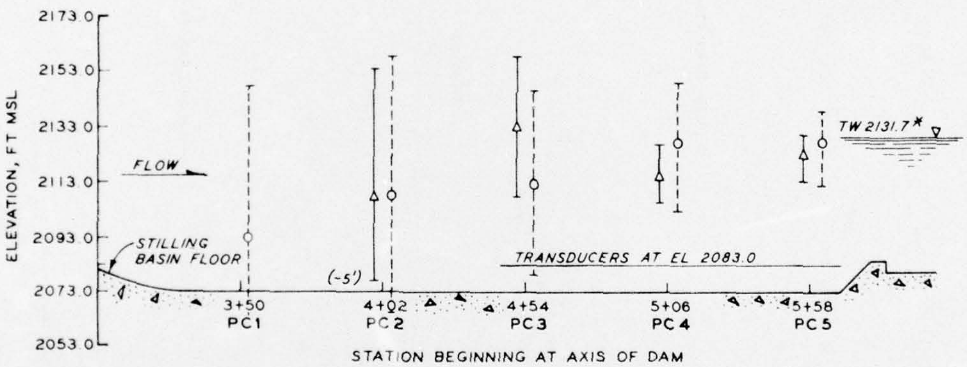
STILLING BASIN WALL PRESSURES

MODEL DISCHARGES 20,000 - 30,000 CFS
PROTOTYPE DISCHARGES 20,000 - 29,000 CFS



TEST 67

MODEL DISCHARGE 40,000 CFS
PROTOTYPE DISCHARGE 37,000 CFS



TEST 68

MODEL DISCHARGE 50,000 CFS
PROTOTYPE DISCHARGE 47,000 CFS**

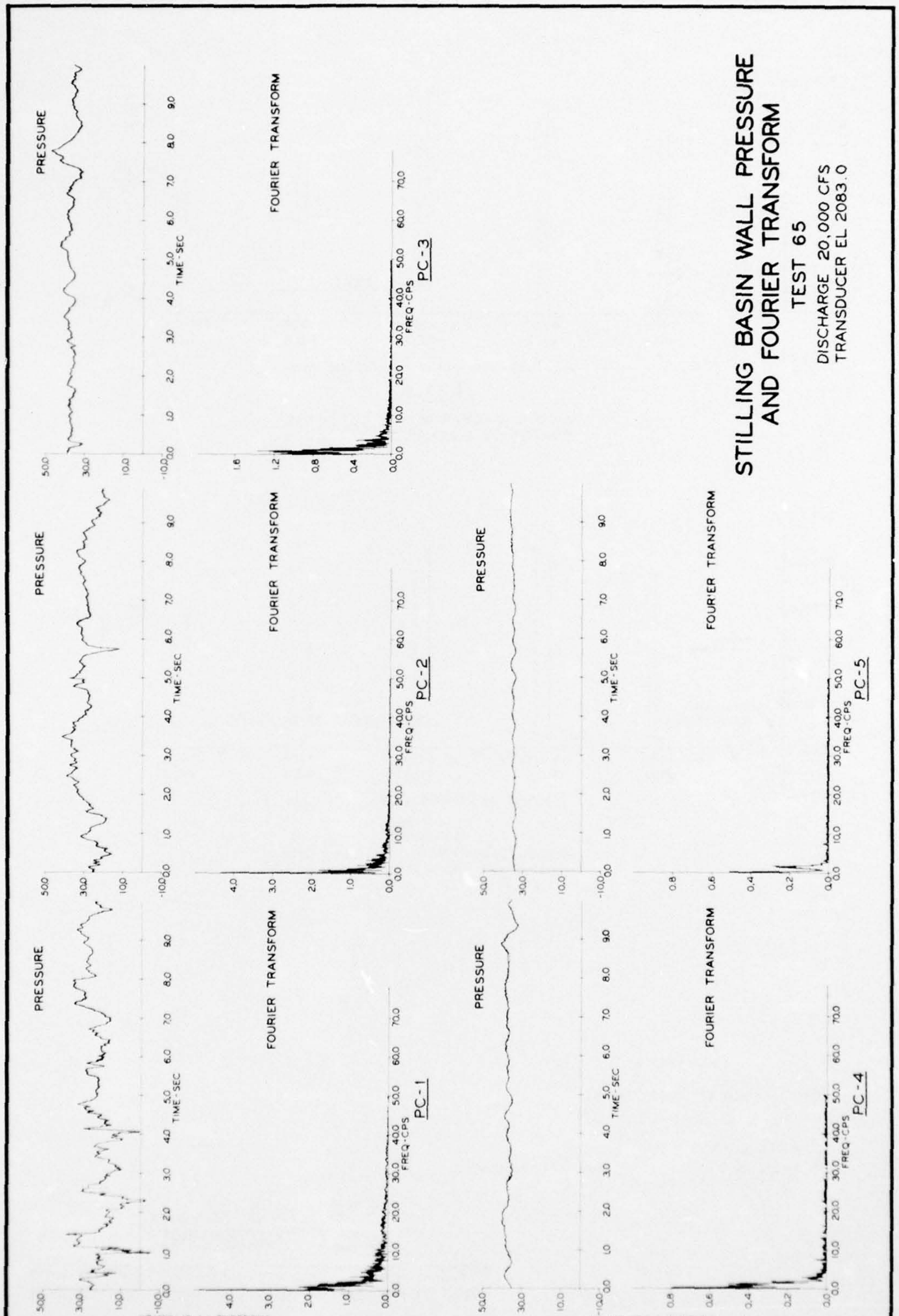
PROTOTYPE — MAX PRES / AVG PRES / MIN PRES — MODEL

* MODEL DATA.

** DISCHARE APPROXIMATE, TEST HALTED DUE TO HIGH FLOW DAMAGE.

STILLING BASIN WALL PRESSURES

MODEL DISCHARGES 40,000 - 50,000 CFS
PROTOTYPE DISCHARGES 37,000 - 47,000 CFS

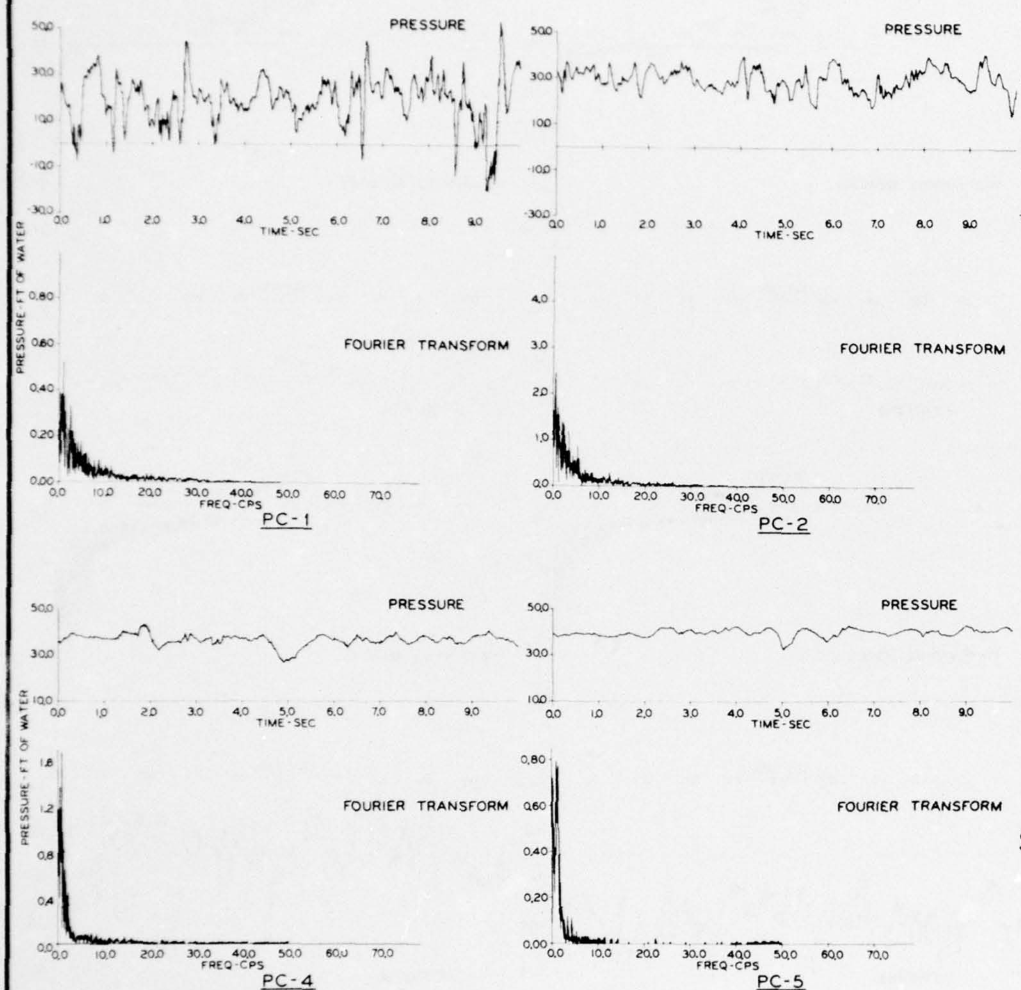


STILLING BASIN WALL PRESSURE AND FOURIER TRANSFORM

TEST 65

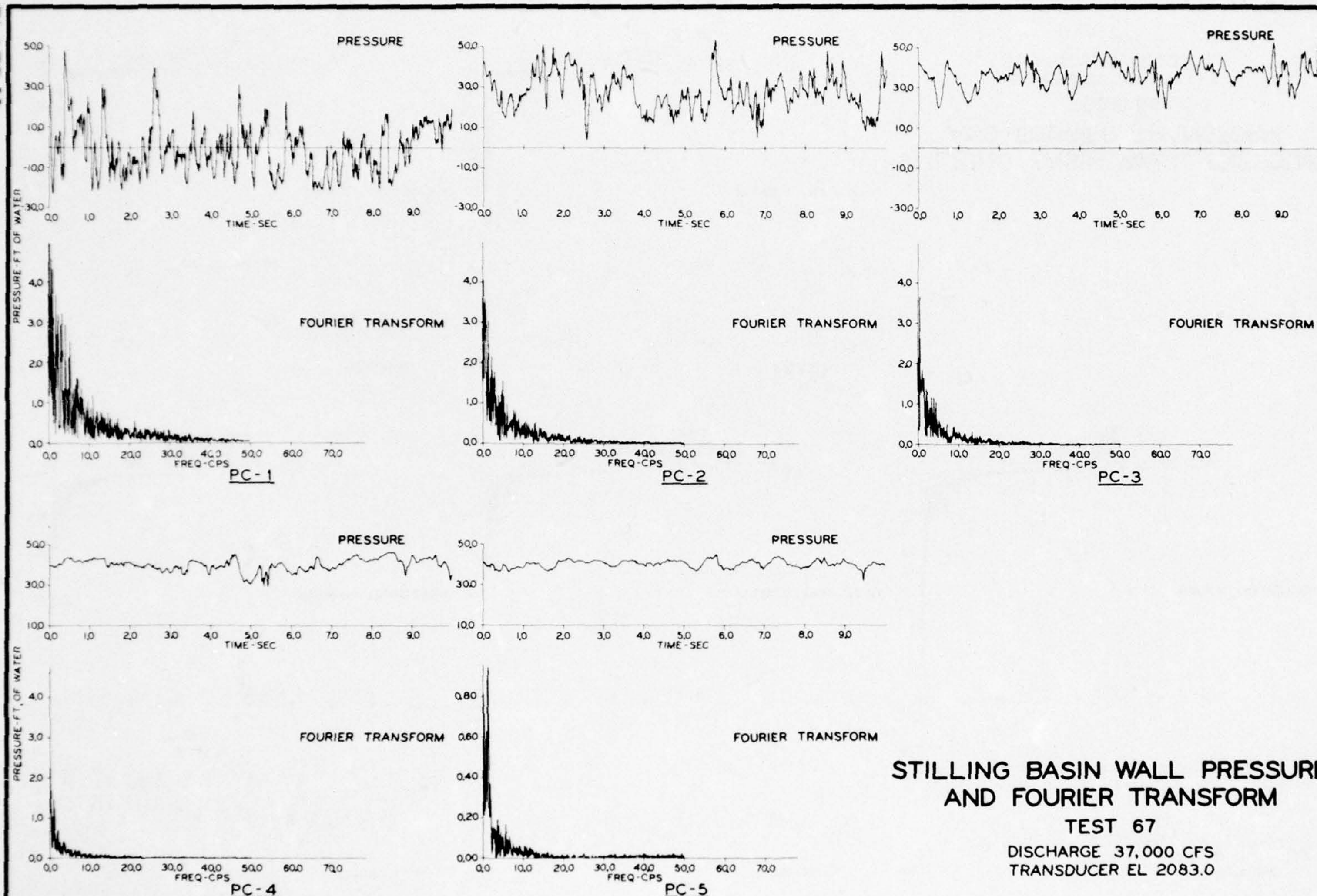
DISCHARGE 20,000 CFS
TRANSDUCER EL 2083.0

PLATE 16

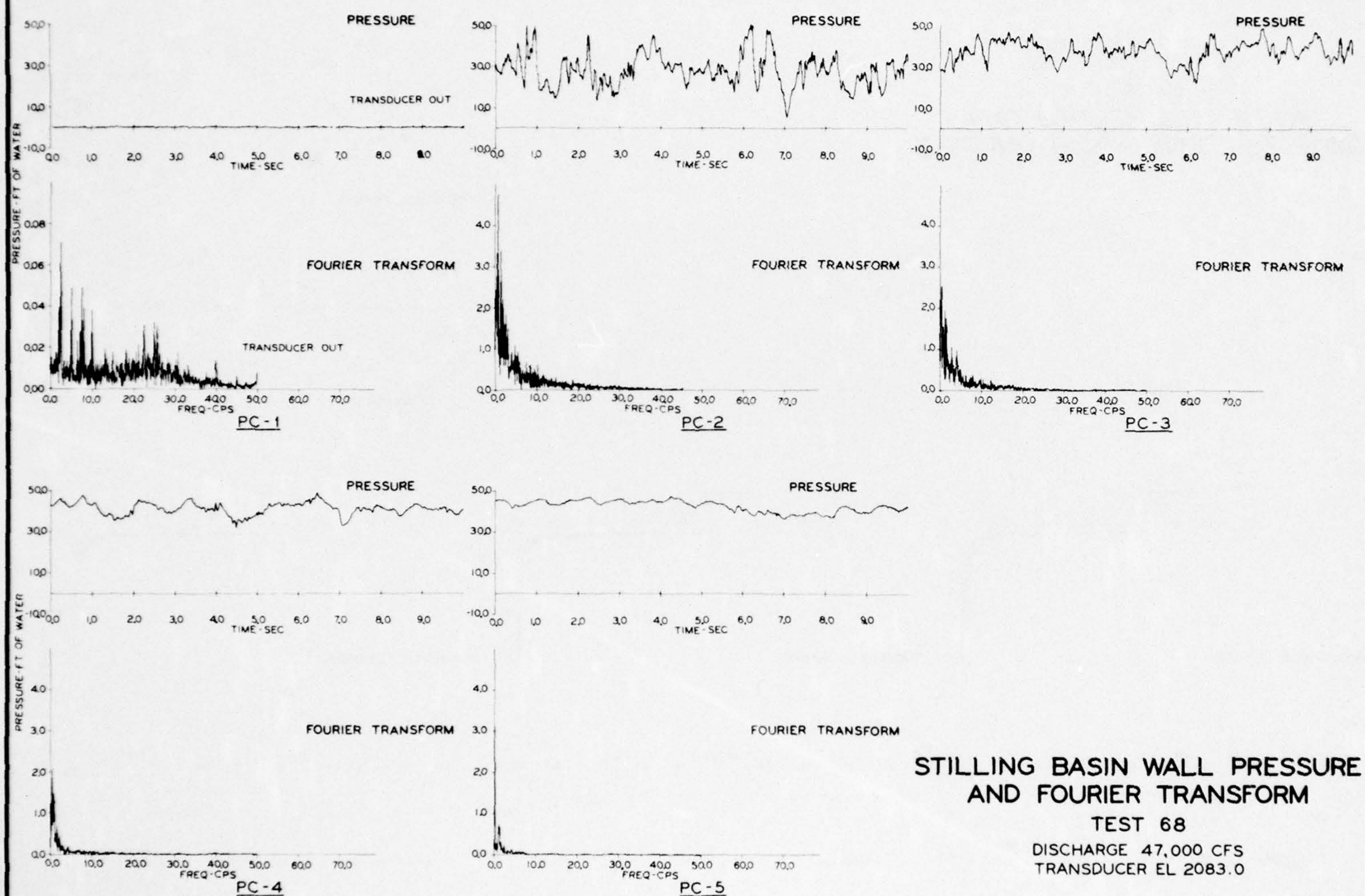


STILLING BASIN WALL PRESSURE
AND FOURIER TRANSFORM
TEST 66
DISCHARGE 29,000 CFS
TRANSDUCER EL 2083.0

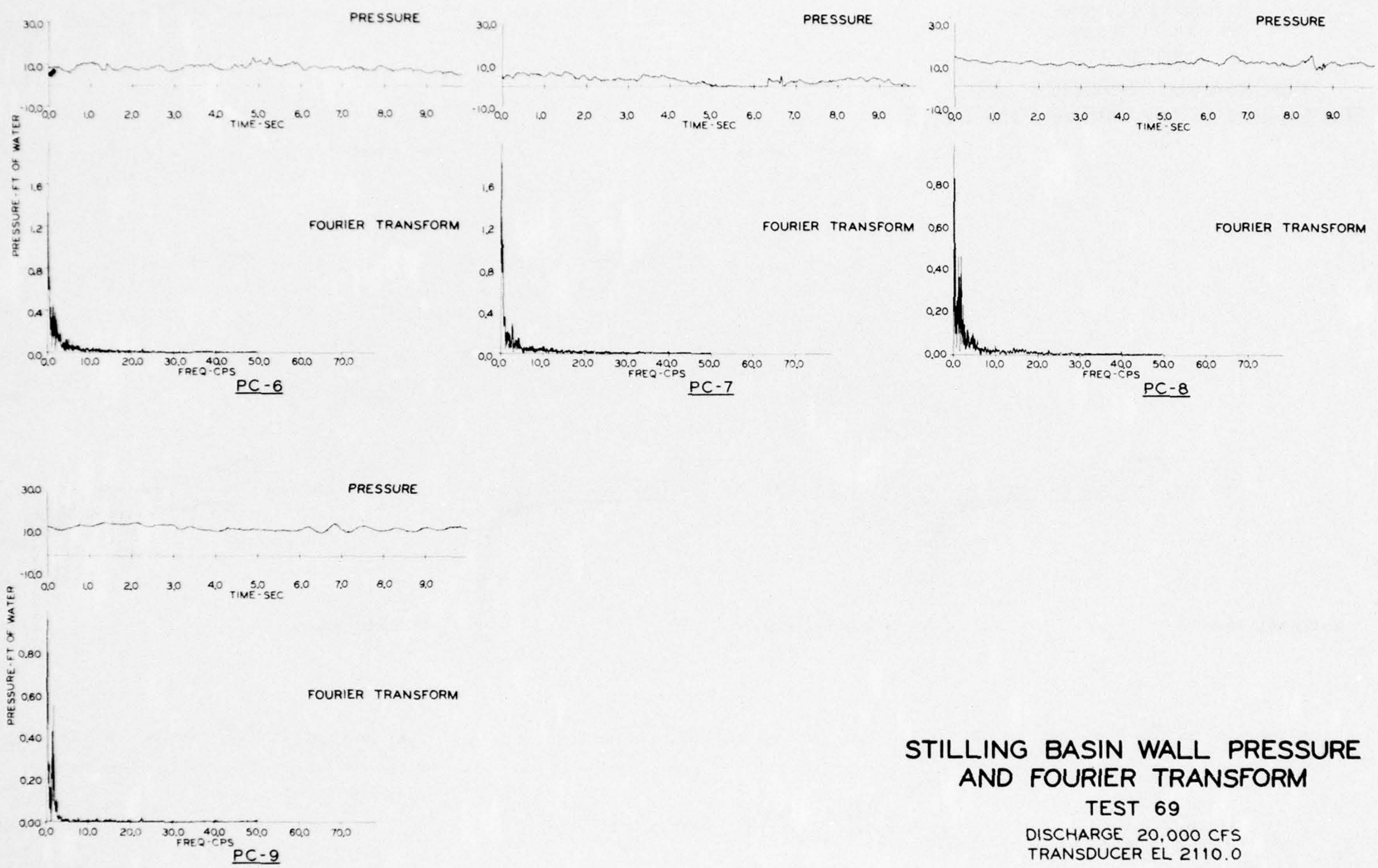
PLATE 18



STILLING BASIN WALL PRESSURE
AND FOURIER TRANSFORM
TEST 67
DISCHARGE 37,000 CFS
TRANSDUCER EL 2083.0



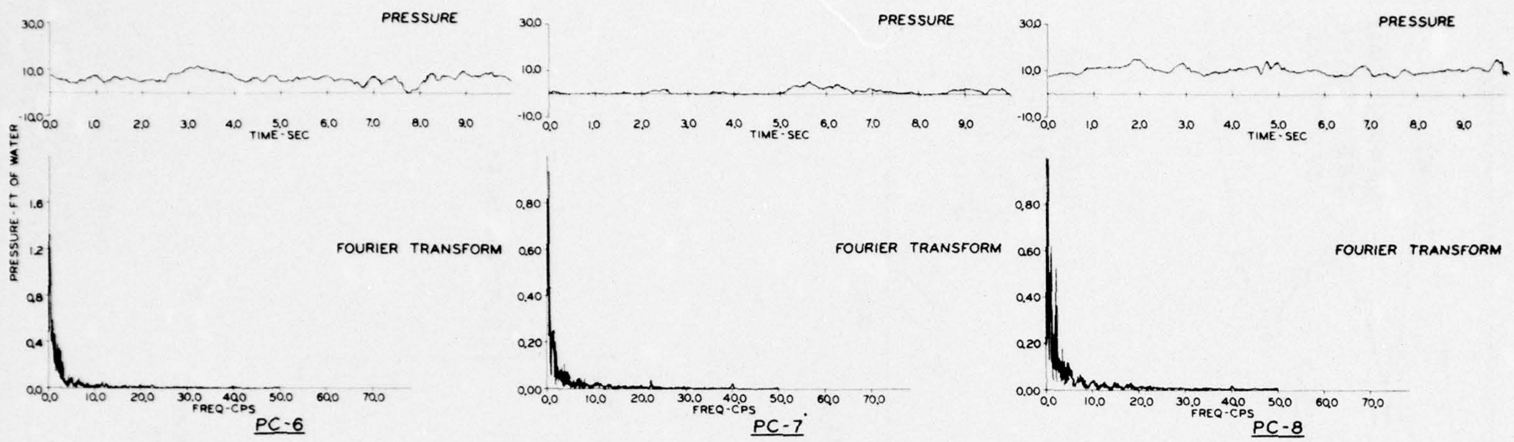
STILLING BASIN WALL PRESSURE
AND FOURIER TRANSFORM
TEST 68
DISCHARGE 47,000 CFS
TRANSDUCER EL 2083.0

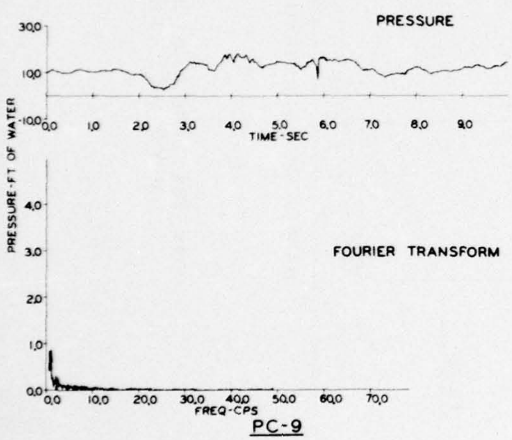


STILLING BASIN WALL PRESSURE AND FOURIER TRANSFORM

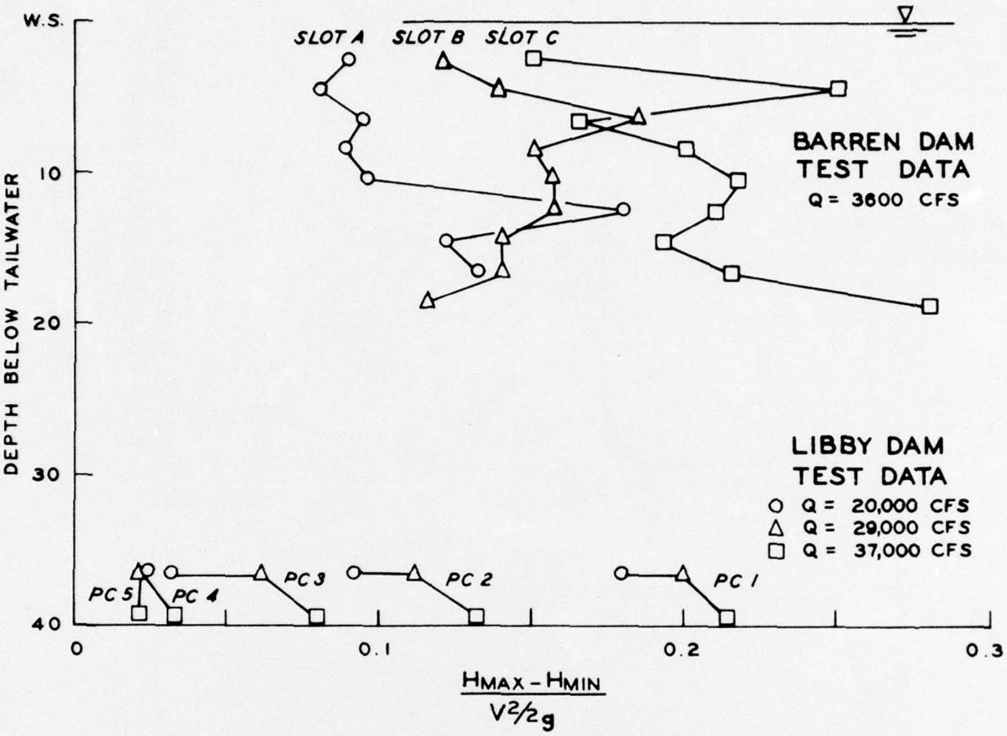
TEST 69

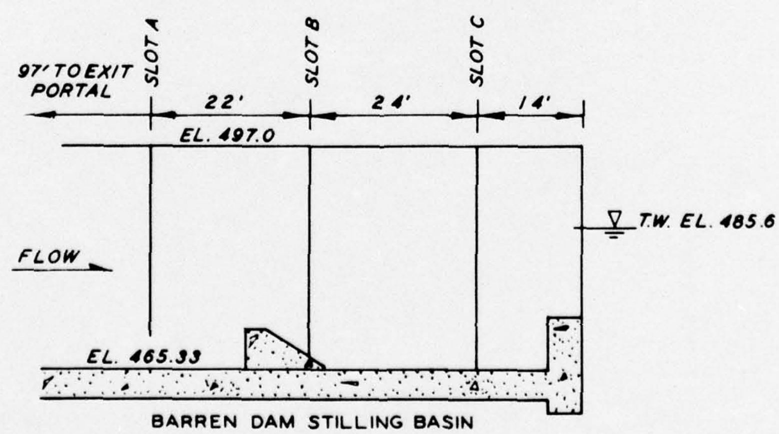
DISCHARGE 20,000 CFS
TRANSDUCER EL 2110.0





STILLING BASIN WALL PRESSURE
AND FOURIER TRANSFORM
TEST 70
DISCHARGE 29,000 CFS
TRANSDUCER EL 2110.0





NOTE: SEE PLATE 1 FOR DETAILS OF LIBBY DAM STILLING BASIN

BARREN AND LIBBY DAMS

STILLING BASIN WALL PRESSURES

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Hart, *Ellis Dale*

Sluice pressures, gate vibrations, and stilling basin wall pressures, Libby Dam, Kootenai River, Montana, by E. Dale Hart [and] Allen R. Tool. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.

1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report H-76-17)

Prepared for U. S. Army Engineer District, Seattle, Seattle, Washington.

Includes bibliography.

1. Cavitation. 2. Gate vibration. 3. Libby Dam. 4. Pressure measurement. 5. Sluice gates. 6. Sluices (Hydraulic engineering). 7. Stilling basins. I. Tool, Allen R., joint author. II. U. S. Army Engineer District, Seattle. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report H-76-17)

TA7.W34 no.H-76-17